CHEMICAL AND ISOTOPIC EVOLUTION OF DISSOLVED INORGANIC CARBON IN GROUNDWATER OF THE OKAVANGO DELTA, BOTSWANA

By

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Abstract: This paper reports the results of a study of the origin and the chemical and isotopic evolution of dissolved inorganic carbon (DIC) in groundwater in the Okavango Delta in semi-arid Botswana. The Okavango Delta is one of the few examples of large river systems where carbon is cycled entirely in the terrestrial system and we hypothesized a river origin for carbon in groundwater. We measured DIC, major ions and the stable carbon isotopes of DIC ($\delta^{13}C_{DIC}$), hydrogen (δD) and oxygen ($\delta^{18}O$) in groundwater. We used our results along with published chemical and isotopic results for groundwater and surface water to assess the origin and evolution of DIC in groundwater in the Okavango Delta. The DIC concentrations increase progressively from surface water to shallow groundwater (<5 m) to deep groundwater (≥50 m) and the DIC concentrations are two to ten times higher in groundwater than in the Okavango River. The $\delta^{13}C_{DIC}$ of the shallow and deep groundwater were lighter than for surface water, suggesting that the carbon if from River water recharge was modified by input of DIC with lighter carbon isotope. The δD and $\delta^{18}O$ for surface waters are enriched by evaporation, and when compared to groundwater, the isotopes distinguish groundwater that is recharged by the evapo-concentrated river water and directly by rain. Despite the differential recharge sources (rain vs. river) with marked isotopic differences, the chemical evolution of the groundwater within the Okavango Delta and surrounding is indistinguishable and is not chemically related to modern day river water and shallow groundwater. We suggest open system carbonate evolution for river and island groundwater and closed system carbonate evolution for deep groundwater. The lack of genetic connection for the chemical evolution between modern day surface water and the deep groundwater suggest that the deep groundwater may not be recharged by present day Okavango River. We conclude that DIC concentrations in groundwater of the Okavango Delta originates from subsurface production of DIC, and is mostly old DIC stored in the groundwater system for long periods of time (>0.8 ka).

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CHAPTER I

INTRODUCTION

1.1 Project Motivation

The storage of carbon in groundwater or release to surface water systems (rivers, lakes, oceans) that interact with the atmospheric $CO_{2(g)}$ reservoir makes groundwater an important part of the global carbon cycle. Our knowledge and understanding of the sources of carbon, and the role of water-rock interactions in carbon transformation in groundwater have been advanced by studies in temperate (e.g., Fritz et al., 1988; Aravena et al., 1992; Aucour et al., 1999; Telmer and Veizer, 1999) and tropical and subtropical (e.g., Cai and Wang., 1998; Raymond and Bauer; 2001; Li-Si-Liang et al., 2010) regions. In contrast, studies of the processes that affect carbon evolution and the cycling of carbon in groundwater of semi-arid and arid environments are limited (e.g., Dincer at al., 1979; Herczeg et al., 1990; Cartwright 2010). Carbon in groundwater in arid environments unlike groundwater in humid temperate and tropical environments is less likely to be discharged to the surface, and thus can be considered as a long term store for carbon.

Of special interest in carbon cycling are endorheic riverine systems in arid environments. Here, carbon transferred from watersheds accumulates at the terminus of the basin. If the watershed is large (>10^3 km^2), then a significant amount of carbon can be stored in endorheic basins. A good example of an endorheic riverine system is the Okavango Delta in the Middle Kalahari Desert in northwestern Botswana (e.g., McCarthy and Ellery, 1998). The Okavango Delta is unique because its watershed is ~530,000 km^2 and spans from the tropical highlands of Angola to the Kalahari Desert (Ellery et al., 2003). What is known as the Okavango River in Botswana flows southeastward from its source for almost 1,600 km before terminating in the Okavango Delta region in Botswana (Nicole and Vorwerk, 2007). Given an annual discharge of approximately 11×10^9 m^3 (McCarthy and Ellery, 1995; Shaw and Nash, 1997; McCarthy et al., 2000) brought into the

Okavango Delta, the amount of carbon in river discharge over time frames of 10^3 years is potentially significant.

There is need to study the chemical and isotopic evolution of carbon in the terminal Okavango River system because the evolution of carbon and the ultimate fate of carbon is not well understood. For example, the carbon in the form of dissolved inorganic carbon (DIC) delivered into the Okavango Delta by river discharge can (1) be cycled between organic and inorganic forms by biological activities (Mladenov et al., 2005), (2) concentrated in river water and exchanged with atmospheric $CO_{2(g)}$ (Akoko et al., 2013), (3) removed from solution as carbonate precipitates onto floodplains, pans and islands (McCarthy et al., 1991) and cycled to the river during flooding events (Akoko et al., 2013), or (4) be transferred to and stored in the groundwater system. The potential transfer of high concentration of solutes (and likely carbon) to groundwater have been demonstrated in studies of groundwater below islands in the Okavango Delta (McCarthy et al., 1993; Bauer-Gottwein et al., 2007, Huntsman-Mapila et al., 2006).

Given the fact that the rate of evaporation in the Okavango Delta exceeds precipitation by a factor of 3 and that about 96% of river discharged into the delta is lost to the atmosphere by evaporation (Dincer et al., 1978; McCarthy, 1990) we expect that very little river water will infiltrate to recharge the deep groundwater (>50 m). To quantify the amount of carbon transferred to the Okavango Delta's local and regional groundwater, the source of DIC (river water vs. soil zone) needs to be identified and its subsequent chemical and isotopic evolution must be understood. Assessing the concentrations of DIC and the $\delta^{13}C_{DIC}$ allows for direct tracing of carbon and provides information on carbon dynamics (carbon fluxes, sources and biogeochemical processes) during the cycling of carbon between reservoirs (e.g., Clark and Fritz 1997; Atekwana and Krishnamurthy 1998; Aucour et al., 1999; Telmar and Veizer 1999).

Our approach in this study involves making measurements of DIC concentrations, major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-}) and the stable carbon isotopes of DIC ($\delta^{13}C_{DIC}$), hydrogen (δD) and oxygen ($\delta^{18}O$) in groundwater. In addition to our data, we use published chemical and isotopic data for groundwater and surface water. Our objectives are to determine (1) the role of river water vs. rain in the recharge to the groundwater system, (2) the source of DIC in groundwater and (3) the evolution of DIC in groundwater. By knowing the source of DIC and the processes that transform carbon in groundwater in the Okavango Delta, the quantitative evaluation of groundwater carbon cycling can be initiated.

1.2 **Previous study**

A number of other studies have been conducted utilizing geochemical parameters to delineate various biogeochemical processes in the Okavango Delta. Some isotope geochemical work have been done using stable isotopes of hydrogen, carbon and oxygen to characterize the Kalahari groundwater by Mazor et al., 1973; Mazor et al., 1977 and Mazor et al., 1980. They attempted a hydrologic, chemical and isotopic study on the groundwater using C-14 and tritium concentrations to determine the groundwater ages. The deep groundwater was generally >4000ka and the tritium concentrations (0.9±0.2 TU) were also indicative of old water. Bauer et al., 2006 also used isotopic and chemical parameters to investigate the effect of river recharge in the groundwater system. They measured isotopic and salinity differences between groundwater and surface water found an increase in the salinity of groundwater recharged by the river water. There are other previous work whose data have been incorporated in to our database for this study (e.g; Dincer et al., 1978; McCarthy et al., 1991; McCarthy et al., 1993; Bauer et al. 2006; Huntsman-Mapila et al., 2006; Bauer-Gottwein et al., 2007; Huntsman-Mapila et al., 2011; Akoko et al., 2012; Mladenov et al., 2013). These previous studies did not analyze carbon concentrations and $\delta^{13}C_{DIC}$ in groundwater and their studies had different objectives. For instance; Bauer-Gottwein et al.(2007) was focused on analyzing the influence of evapo-concentration on the density driven flow and geochemical reactions within the Islands. Akoko et al. (2012) investigated carbon cycling within the riverine system and found out that there is an increase in DIC concentration and $\delta^{13}C_{DIC}$ down the river profile from the proximal to the distal end of the delta. Huntsman-Mapila et al. (2011) focused on the distribution of Arsenic (As) in the island groundwater and the relationship between its distribution and the major ions concentration. They found a continuous increase in As with major ions and interpreted this to be caused by evaporation, transpiration and competitive interaction between HCO_3^- and As for the same sorption sites as pH increases. Generally, none of the studies was focused on integrating the geochemical behavior of all the reservoirs and how carbon is cycled within them. In this study, we explain the source of carbon in the groundwater and how the different reservoirs (island groundwater, river water, shallow groundwater and deep groundwater) interact with each other in contributing to the big picture of carbon cycling in the Okavango Delta. Also, compiling data of multiple sampling times and earlier sampling periods will therefore capture water evolution over space and time. Our study does not replicate previous studies but rather brings out a comprehensive geochemical analysis of the behavior of carbon in this system over relatively long term periods.

CHAPTER II

STUDY AREA

The Okavango Delta in semiarid NW Botswana **(**Fig. 1) is characterized by a fault-bound trough Panhandle region and a delta region (McCarthy and Metcalfe, 1990). The lower portion of the Okavango Delta is an alluvial fan of approximately 30,000 km^2 in size, consisting of about 6,000 km^2 of permanent swamps and another 6,000 km^2 to 12000 km^2 of seasonal swamps (McCarthy et al., 1991; McCarthy and Ellery 2005; Bauer et al., 2006). The Okavango River forms a distributary system on the alluvial fan in the fault-bounded trough of the Okavango Rift Zone (ORZ), a nascent southwestern branch of the East African Rift System (e.g., Modisi et al., 2000; Kinabo et al., 2007; Bufford et al., 2012). The bedrock in the region is predominantly Precambrain crystalline igneous and metamorphic rocks of the Damara and Ghanzi-Chobe orogenic belt (Benson, 2000) which are exposed to the northwest and southeast of the Okavango Delta. The surficial geology in and around Okavango Delta region consists of a thick covering of Quaternary Kalahari alluvium and recent sediments composed of lacustrine, fluvial and deltaic sediments 300 to 600 m thick (McCarthy et al., 1993; Ringrose et al., 2009; Huntsman-Mapila et al., 2005; Kinabo et al., 2012). The sediments contain significant proportions of quartz, feldspars and clays cemented by carbonates and silica (McCarthy and Metcalfe 1990; McCarthy and Ellery, 1995; Huntsman-Mapila et al., 2005). Calcretes and silcretes are well developed and overlie sediments especially beyond the Okavango Delta proper (McCarthy et al., 1993; Kampunzu et al., 2000).

The piezometric surface in the groundwater of the Okavango region shows that the water table beneath the delta is shallow and becomes deeper away from the flood plain (McCarthy, 2006;

Milzow et al., 2009), which suggest that there is a greater amount of shallow groundwater recharge occurring within the delta (McCarthy, 2006). There are a series of numerous islands found in the Okavango Delta and there is a net flow of shallow groundwater from the delta region towards the islands (McCarthy et al., 1991; Wolski and Savenije, 2006; McCarthy, 2006; Huntsman-Mapila et al, 2011). The shallow groundwater flow to the islands is driven by evapo-transpiration (Wolski and Savenije, 2006), which leads to the accumulation of dissolved solutes and precipitation of solutes beneath the island (Huntsman-Mapila et al., 2011). Evapotranspiration induces chemical precipitation from the groundwater which leads to the sequestration of carbon as carbonate minerals (McCarthy et al., 1986). The islands therefore modify the chemistry of the river water and shallow groundwater and controls chemical sedimentation (McCarthy and Metcalfe, 1990; McCarthy et al., 1991; Bauer-Gottwein et al., 2007). In order to have an understanding of the major changes in the groundwater and the overall mechanism and processes that occur within the reservoirs, it is important to sample groundwater from all the various reservoirs including islands. The processes that control the movement of water and solutes are the same that controls the cycling of carbon and this in turn controls the movement of carbon (DIC) from reservoir to reservoir.

The climate of the Okavango Delta region is hot and dry with a rainy season that spans from November to March and a dry season that spans from April to October. Mean temperatures of 35^0C and 25^0C characterize the rainy and dry seasons, respectively (McCarthy and Ellery, 1993; Mbongwe et al., 2003; Smith et al., 2009). The mean annual rainfall is 450 mm/year (Sawula and Martins, 1991; Ellery at el., 1993; McCarthy and Ellery, 2005; McCarthy 2006; Milzow et al., 2009) and potential evapotranspiration estimated at 1672 mm/year exceeds annual precipitation by a factor of 3 (Wilson and Dincer 1976; Dincer et al., 1978; McCarthy, 1990). The Okavango Delta region receives an annual river inflow of 11×10^9 m^3 and 5×10^9 m^3 in rainfall (McCarthy and Ellery, 1995; Shaw and Nash, 1997; McCarthy et al., 2000). From a water balance stand point, river discharge is the dominant source of groundwater recharge in the Okavango Delta region (McCarthy et al 2000; DWA, 2003; McCarthy, 2006). The Okavango Delta has several faults (Gumare, Tsau, Lecha, Kunyere, Thamalakane and Mababe) within ORZ that provide conduits by which river water may recharge groundwater beyond the Delta (Bufford et al., 2012).

CHAPTER III

METHODOLOGY

3.1 Sampling and analyses

We measured the physical, chemical and isotopic parameters from shallow groundwater, deep groundwater and island groundwater (Fig. 1). Shallow (<5 m) groundwater was collected from discrete depths from piezometers installed at 0.25 m intervals in the floodplain in the distal portion of the Okavango Delta in Maun and Toteng. Deep groundwater (>50 m) was collected from water supply wells operated by the Botswana Department of Water Affairs (DWA) within the distal portion of the Okavango Delta and several villages in the region. Groundwater samples from the shallow piezometers were pumped to the surface using a peristaltic pump. Groundwater from the water supply wells was pumped to the surface using high capacity water supply pumps operated by the staff from DWA. We sampled island groundwater from Okavango Research Island (See Table S1 for longitude and latitude locations).

Readings for pH, temperature, electrical conductivity (EC), total dissolved solids (TDS) and oxidation-reduction potential (ORP) were taken at each sampling station using a Yellow Spring Instrument (YSI) multi-parameter probe calibrated according to manufacturers' recommendations. Water collected for chemical and isotopic analyses were filtered through 0.45 μM syringe filters. Samples for anions were stored without acidification in 30 mL high-density polyethylene **(**HDPE) bottles while samples for cations were stored in 60 mL HDPE bottles which were acidified with high purity HNO_3 to a pH <2. The samples for DIC extraction and $\delta^{13}C_{DIC}$ measurements were collected in 15 mL pre-evacuated vacutainer tubes pre-loaded with 1 mL 85% H_3PO_4 and magnetic stir bars (Atekwana and Krishnamurthy, 1998). Samples for stable isotopes of hydrogen (δD) and oxygen ($\delta^{18}O$) analysis were collected in 20 ml scintillation vials with inverted cone closure. After collection, all samples were protected from sunlight and stored under cool conditions. The samples were kept cool for 1 to 4 weeks before being transported to the United States where they were stored in a refrigerator at 4 °C until analysis.

In the field, alkalinity was determined by titration with sulfuric acid (Hach, 1992). Cations (Na^+, K^+, Mg^{2+}, Ca^{2+}) and anions (Cl^-, NO_3^- and SO_4^{2-}) were analyzed by ion chromatography using a Dionex ICS-3000. The DIC was recovered as $CO_{2\,(g)}$ cryogenically from samples under vacuum using the technique of Atekwana and Krishnamurthy (1998). The $CO_{2\,(g)}$ concentrations were determined nanometrically and subsequently sealed in Pyrex tubes. The $\delta^{13}C$ of the $CO_{2\,(g)}$ was measured using a Thermo Finnigan Delta Plus XL isotope ratio mass spectrometer. Measurement of the δD and $\delta^{18}O$ for the water samples was carried out by the technique of Gehre et al. (2004) using a high temperature conversion elemental analyzer (TC/EA) coupled to Thermo Finnigan Delta Plus XL isotope ratio mass spectrometer. The isotope ratios are reported in the delta notation (δ) in per mil (‰) relative to international standards:

$$\delta\ (‰) = ((R_{sample} - R_{standard}) / R_{standard}) * 1000$$

where R is the D/H, $^{13}C/^{12}C$ or $^{18}O/^{16}O$ ratio in the sample and standard. The $\delta^{13}C$ is reported relative to Vienna Pee Dee Belemnite (VPDB) standard, while the δD and $\delta^{18}O$ are reported relative to Vienna Standard Mean Ocean Water (VSMOW). In-house standards routinely measured have precision of better than 0.1‰ for $\delta^{13}C$ and $\delta^{18}O$ and 2.0‰ for δD.

We used additional data for shallow groundwater, deep groundwater, island groundwater and surface water in the Okavango Delta region from the published literature (Dincer et al., 1978; McCarthy et al., 1991; McCarthy et al., 1993; Bauer et al. 2006; Huntsman-Mapila et al., 2006; Bauer-Gottwein et al., 2007; Huntsman-Mapila et al., 2011; Akoko et al., 2012; Mladenov et al., 2013). For groundwater samples from the published literature, we classified them as deep and shallow based on sampling depths. We assumed that all groundwater collected beyond the delta were deep because of deep groundwater table from published studies (e.g., McCarthy et al., 1993). For wells within the delta that did not have depths, we guessed their depths based on our perceived purpose for the well (e.g., hand dug wells were considered shallow) and water supply wells were considered deep.

CHAPTER IV

RESULTS AND DISCUSSION

The chemical and isotopic data for the water samples we measured were combined with published data from the literature and evaluated. A total of 363 individual water sample results were compiled in the database (Table S1 and S2); however, not all the samples were measured for all the parameters. The groundwater samples were collected over different time periods from 1977 to 2012 and some locations were sampled multiple times. Samples from surface water (Okavango River and distributaries, lagoons, lakes and pans) were collected at different locations and seasons, and some of the locations were sampled multiple times. We argue that for the purpose of interpretation, there should be no disadvantage treating each sample as independent, as together, they capture water evolution over space and time. Summary statistics (minimum, maximum, average, standard deviation and number of samples) of parameters for the shallow groundwater, deep groundwater, island groundwater and surface water are listed in Table 1.

The DIC concentrations and $\delta^{13}C_{DIC}$ averaged 18.2 ±6.8 mg C/L and -9.9 ±0.8‰ for shallow groundwater, 73.3 ±15.3‰ mg C/L and -9.8 ±1.1‰ for deep groundwater, 179.4 ±276.1 mg C/L and -4.1 ±2.5‰ for island groundwater and 8.2 ±3.8 mg C/L and -8.1 ±2.1‰ for surface water. The DIC concentrations relative to the $\delta^{13}C_{DIC}$ for the different groups of samples is displayed in Figure 2. The DIC and $\delta^{13}C_{DIC}$ in the Okavango River are higher in the distal end compared to the Panhandle region where river water flows into the Okavango Delta (Akoko et al., 2012). The DIC concentrations for shallow groundwater and deep groundwater are higher compared to river water and the groundwater samples have correspondingly lower $\delta^{13}C_{DIC}$ (Fig. 2). Groundwater from the

Okavango Delta islands have higher DIC concentrations compared to river water and show both higher and lower $\delta^{13}C_{DIC}$ (Fig. 2) compared to river water .

4.1. Source of DIC in groundwater

4.1.2 Conceptual model

We devised a conceptual model (Fig. 3) as a way to explore how DIC originates and evolves before and during the groundwater recharge process. This model shows that the main ways of introducing DIC into the groundwater is through riverine (surface water) recharge and rainfall recharge via the unsaturated zone. Prior to recharge of groundwater by surface water (Fig. 3), the DIC is potentially affected by (1) water column respiration and photo-oxidation that add carbon to the DIC pool and photosynthesis that removes carbon from the DIC pool, (2) carbonate precipitation on floodplains and islands which remove carbon from the DIC pool and dissolution of carbonates from floodplains and islands that add DIC, (3) $CO_{2(g)}$ evasion that transfers carbon from the DIC pool to the atmosphere, (4) evapotranspiration which causes increases in the DIC concentrations (Akoko et al., 2013) and (5) carbon exchange in the DIC pool with atmospheric $CO_{2(g)}$ with essentially no DIC concentration change. The multiple processes that act on the riverine DIC occur at different magnitude over variable temporal and spatial scales. The study by Akoko et al. (2013) suggest that the important factors that affect the DIC evolution in Okavango River especially in the distributaries in the lower portion of the delta are evapo-concentration and carbon exchange between DIC and atmospheric $CO_{2(g)}$. These factors cause increases in the DIC concentrations and the $\delta^{13}C_{DIC}$ in the downriver direction. The downriver increase in DIC concentrations with increase in the $\delta^{13}C_{DIC}$ is observed as an overall positive relationship in Figure 2. This indicates that groundwater recharged by river water across the Okavango Delta will have variable DIC concentration and $\delta^{13}C_{DIC.}$

Where the evapo-concentrated surface water (Okavango River) does not constitute the main source of groundwater recharge (Fig. 3), DIC that is transferred to rain water that infiltrates the soil and sediments through the unsaturated zone comes from and dissolution of atmospheric $CO_{2(g)}$ and soil $CO_{2(g)}$ (Mazor et al., 1980) and from carbonate and silicate weathering (Fig. 3). For an infiltrating solution that is oversaturated with respect to the mineral calcite, DIC can be removed by precipitation. The effect of the dry environment on evaporation and the decrease in transpiration due to scanty vegetation in the region beyond the floodplains of the Okavango Delta (McCarthy et al., 1991) may affect the chemical and isotopic evolution of water in the unsaturated zone during groundwater recharge (Mazor et al., 1980).

From the conceptual model, we expect that both the DIC concentrations and the $\delta^{13}C_{DIC}$ groundwater from river water or rain will be significantly different. In addition, the surface evaporative processes that affect water isotopes will enrich river water to a greater degree than rain water. This is clearly observed in studies of surface water where the effect of evaporation in part controls the downriver increases in the DIC concentrations and enriches the δD and $\delta^{18}O$ (e.g., Dincer et al., 1979; Akoko et al., 2013). We can therefore use the DIC concentrations and $\delta^{13}C_{DIC}$ and the δD and $\delta^{18}O$ compositions as tracers to evaluate the source of groundwater recharge, and by implication the source(s) of DIC.

4.1.2 Role of river vs. rain in groundwater recharge

In a plot of the $\delta^{18}O$ vs. δD (Fig. 4), surface water samples lie on the trend of the Okavango Delta Evaporation Line (ODEL) of Dincer et al. (1979). We observe that all the shallow groundwater and the deep groundwater samples also lie on the ODEL. We collected shallow groundwater below distributary floodplains in the distal portion of the Okavango Delta (Maun and Toteng) in regions where recharge was predominantly by recent evapo-concentrated river water. The isotopic composition of the shallow groundwater is enriched (0.1 to 2.7 ‰ for $\delta^{18}O$ and -5 to 7 ‰ for δD) and falls within the range of evapo-concentrated surface water (-7.2 to 17.4 ‰ for $\delta^{18}O$ and -47.4 to 73.3 ‰ for δD) (Fig. 4). This similarity in isotopic composition confirms that shallow groundwater is recharged by river water. Since shallow groundwater can be directly recharged by river water, we can use this as evidence that some locations of the deep groundwater also have an evapo-concentrated water source. The same can be said for island groundwater as studies show that it is recharged by evapo-concentrated river water (McCarthy and Ellery, 1994; Huntsman-Mapila et al., 2006; Peter Bauer-Gottwein et al., 2006; McCarthy et al., 2012, Mladenov et al., 2013). The $\delta^{18}O$ and δD of island groundwater lie on the ODEL within the region of surface water (Fig. 4).

Some of the deep groundwater samples collected away from the Okavango Delta have $\delta^{18}O$ and δD that lie towards the intersection of the ODEL and the Global Meteoric Water Line (GMWL; Craig and Gordon, 1965). The $\delta^{18}O$ and δD of these samples do not extend to the local meteoric water line (LMWL) constructed from Maun (19°59'39.01"S and 23°25'6.24"E) rain collected in rainy season of 2012-2013 (Atekwana, unpublished) as expected for unevaporated rain. Nevertheless, there are Maun rain samples that cluster in the region where the groundwater samples plot (Fig. 4). The $\delta^{18}O$ vs. δD relationship can be used to argue that groundwater recharged exclusively by rain lie on the most negative region of the ODEL at the intersection with the GMWL. The $\delta^{18}O$ and δD of these deep groundwater samples have a range that is similar for groundwater from Orapa, Botswana, 500 km east of the Okavango Delta where recharge is exclusively by rain (Mazor et al., 1977). The Orapa groundwater (shallow as well as deep) derive their $\delta^{18}O$ and δD from rainwater that infiltrated directly into the groundwater sufficiently fast such that the isotopic composition is not affected by evaporation (Mazor et al., 1977). The recharge of deep groundwater away from the Okavango Delta does not occur regularly and continuously, but is restricted to periods of unusually heavy rainfall when the precipitation tend to a have lighter isotope composition (Vogel and Van Urk, 1974). Some of the Maun rain samples do not fit the model of the local meteoric water line; some of the rain samples were enriched than the groundwater water samples recharged by rain water which is an indication of its source. The rain responsible for groundwater recharge in the Okavango is from the Atlantic Ocean (lighter isotopic composition than the Indian Ocean) (Vogel and Van Urk, 1974). The deep groundwater samples that lie further to the right of this group on the ODEL between the GMWL and shallow groundwater are a mixture of rain recharged and evaporated surface recharged groundwater; the degree of shift to more positive $\delta^{18}O$ and δD values depends on the contribution of evaporated surface recharged to the groundwater.

We devised a conceptual model to explain the recharge pattern of groundwater in the Okavango Delta (Fig. 5). Our conceptual model is created based on the topography and water table model of Milzow et al. (2009). The model shows that the Okavango River recharges only the shallow groundwater and there is limited recharge for the deep groundwater. Given the fact that the rate of evaporation in the Okavango Delta exceeds precipitation by a factor of 3 and about 96% of river discharged into the delta is lost to the atmosphere by evaporation (Dincer et al., 1978; McCarthy, 1990) we expect limited recharge of deep groundwater (>50 m) by modern day Okavango River water. Diffuse groundwater recharge is limited in the Kalahari region over a sand cover of more than about 4 m deep from rains averaging 450 mm/year (Jennings, 1974; Foster et al., 1982). However, it is suggested that active recharge occurs adjacent to major pan depressions, fossil valleys (Jensings, 1974; Mazor 1982; De Vries, 1984) and through fissures and zones of bioturbation (Mazor, 1982). Studies has also shown that there were several ancient lake conditions in this region ranging from 0.8 ka to ~40 ka with series of warmer phases (Hunstamn-Mapila et al., 2006), however the Lake events of ~4000 years were sufficient to cause recharge of the deep groundwater in this region which were consistent with the events in Palaeo-Lake Makgadikgadi (Ringrose et al., 2005; Mazor et al., 1982). The ^{14}C contents of the deep groundwater show that their age is about several thousand (~4000) years old (Mazor et al., 1974; Mazor et al., 1982). Therefore the shallow water circulation system is recharged by modern day Okavango River while the deep groundwater is recharged by past wet periods. The fact that the source of recharge of deep groundwater may not be modern rain or river water has implication for solute and carbon transfer from modern day Okavango River to deep groundwater.

4.2 Chemical evolution of groundwater

4.2.1 Major ions

The chemical evolution of DIC in groundwater is intimately tied to the chemical evolution of the major ions. The proportion of anions and cations in the water samples are plotted in a piper diagram (Fig. 6). Surface water, is predominantly Ca-Na-HCO_3 type with just a few samples in the Na-Ca cation facies. Shallow groundwater recharged directly by modern-day Okavango River is also predominantly Ca-Na-HCO_3 type. Island groundwater has Cl-SO_4 to Cl-HCO_3^- to HCO_3^- anion facies with the cation facies varying from Ca-Mg to Ca-Na to Na-Ca to Na-K. In remarkable contrast, the dominant cation facies of deep groundwater is Na-K which has anion facies that range from HCO_3 to HCO_3-Cl-SO_4 to Cl-SO_4-HCO_3. Our results for the water types match those of Huntsman-Mapila et al. (2006) for surface water and deep groundwater, while our island groundwater samples match those of Huntsman-Mapila et al. (2011).

To explain the chemical evolution of deep groundwater with respect to the major ions, we use support from the $\delta^{18}O$ and δD. Even though the $\delta^{18}O$ and δD of the deep groundwater samples in the floodplain region of the Okavango River distributaries show recharge from evaporated water (Fig. 4), it appears that surface and deep groundwater have different chemical evolutions (Fig. 6). Also, the chemical behavior of the deep groundwater is not governed by their geographical positions because samples collected from within and out of delta regions show a similar chemical evolution. The chemical evolution thus shows that deep groundwater is not related genetically to modern day river and shallow groundwater.

The chemical evolutionary behavior driven by evapo-concentration is exhibited by island groundwater which evolves across Mg-Ca to Ca-Mg to Ca-Na to Na-Ca to Na-K cation facies (Fig. 6) with the eventual precipitation of trona ($Na_3(CO_3)(HCO_3).2H_2O$) at the end of the chemical evolution (e.g., McCarthy et al., 1991; McCarthy and Ellery, 1995; Shaw and Nash, 1997). Island groundwater of the Mg-Ca cation facies also evolves by evapo-concentration which leads to enrichment from HCO_3 to Cl to SO_4 facies (Fig. 6). The HCO_3-Cl-SO_4 to Cl-SO_4-HCO_3 evolution for the deep groundwater samples could be explained if there is a source of SO_4^{2-} added to groundwater from the dissolution of gypsum. We also observe that some of the island groundwater samples evolve progressively with increase concentrations of Cl and SO_4^{2-} (Fig. 6). Mazor et al. (1980) suggests that the most likely source of SO_4^{2-} in Kalahari groundwater is from the H_2S-rich mist that is common along south-west Africa/Namibia which originates from the decomposition of the dense fauna that thrives in the cold Benguela Current. The reaction of the H_2S-containing water with the country rocks along the coast of the Namib Desert forms gypsum crusts. Winds that blow towards the Kalahari can carry the sulfate that is washed out by the rains; the H_2S mist is also observed several tens of kilometers inland (Mazor et al., 1980). The precipitation of trona can also explain the continuous evolution away from the HCO_3 anion facies and progressively towards HCO_3-Cl- SO_4 to Cl- SO_4 -HCO_3 for deep groundwater samples and some island groundwater samples. Huntsman et al. (2005) suggests that neither the SO_4^{2-} nor the Cl-dominated groundwater originate from the Okavango River recharge but rather from factors independent of Okavango River, although these factors were not explained. This is further confirmed by the absence of the SO_4^{2-} dominated facies in the modern day shallow groundwater collected below the floodplains (blue filled circles; Fig. 6). The presence of SO_4^{2-} can also be explained by organic matter degradation (indicated by decrease in $\delta^{13}C_{DIC}$ composition with depth (Fig. 2)) which has been observed on Okavango Delta islands (Mladenov et al., 2013).

4.2.2 Carbonate Chemistry

The effects of evaporative concentration and rock-water interaction influencing the geochemical evolution of groundwater is shown in a plot of the TDS vs. the $\delta^{18}O$ (Fig. 7a) and TDS vs. the sum of cations ($Na^+ + K^+ + Ca^{2+} + Mg^{2+}$) (Fig. 7b). From the TDS-$\delta^{18}O$ relationship, the increase in $\delta^{18}O$ with increase in TDS observed in surface water breaks down at a TDS value of about 100 mg/l. The increase in TDS for the island groundwater and deep groundwater are not accompanied by increase in $\delta^{18}O$ as observed in surface water. The increasing TDS with little effect on the $\delta^{18}O$ of island groundwater and deep groundwater may be from evapo-concentration by transpiration and/or water-rock interactions. Although there is evidence that island groundwater evolution is influenced by evapo-concentration (McCarthy et al., 1991; Wolski, and Savenije, 2006; Bauer-Gottwein et al., 2007; McCarthy et al., 2012), the $\delta^{18}O$ suggests that this may only be related to transpiration, as transpiration has no fractionation effect on the isotopes of water (Farquhar et al., 1989; Walker and Richardson, 1991).

The positive increase in the TDS with increase in the major cations makes the effect of evapo-concentration indistinguishable from the effects of water-rock interaction (Fig. 7a vs. Fig. 7b). The lack of distinction of the effect of evapo-concentration relative to rock-water interaction in controlling the chemical evolution of surface water and groundwater is also observed in plots of the TDS vs. alkalinity (Fig. 7c) and TDS vs. DIC (Fig. 7d). The relationships between TDS and alkalinity and TDS and DIC suggest that the processes affecting the cation evolution appears to have a similar effect on the DIC evolution.

Within the groundwater system, DIC can evolve by processes which add carbon to the DIC pool such as respiration of organic matter followed carbonate (Eqn. 1) and silicate (Eqn. 2) weathering. The removal of carbon from the DIC pool in groundwater by carbonate precipitation occurs from saturation with respect to the carbonate mineral phase (Fig. 3).

$$CaCO_3+CO_2+H_2O \leftrightarrow Ca^{2+}+2HCO_3^- \quad (1)$$

$$2NaAlSi_3O_8+11H_2O+2CO_2 \leftrightarrow Al_2Si_2O_5(OH)_4+2Na^++2HCO_3^-+4H_4SiO_4 \quad (2)$$

A much greater number of samples from the Okavango Delta have values for alkalinity (n=330) compared to DIC (n=174). Nevertheless, we can compare the carbonate evolution as depicted by alkalinity and DIC concentrations relative to changes in pH and the major cations. Groundwater chemistry in the Okavango Delta is strongly controlled by reactions involving carbonates since carbonates are an essential component of aquifer sediments (Huntsman-Mapila et al., 2011). A major control of the carbonate evolution is the pH of the solution. Changing solution pH can be used to infer the dominant carbonate species in solution or the redistribution of the carbonate species during carbonate evolution (e.g., Stumm and Morgan, 1996). Surface water samples show a broad range of pH (4.9-9.9) and alkalinity (Fig. 8a) which is similarly reflected in the pH-DIC relationship (Fig. 8b). The increase in the alkalinity with increase in pH has been observed in the longitudinal profile of the Okavango River (Hutton and Dincer, 1976; Summerfield, 1982; Sawula and Martins 1991; Akoko et al, 2013). Although the increases in alkalinity and DIC are explained by evapo-concentration (e.g., Akoko et al., 2013), the increasing pH during evapo-concentration to the point of carbonate precipitation has been observed on island surface water and island groundwater (McCarthy et al., 1991; 2012). Shallow groundwater samples show that there is a greater increase in the pH relative to increases in alkalinity (Fig. 8a) and DIC (Fig. 8b). Similarly, deep groundwater shows a wide range in pH change and a rather narrow change in alkalinity and DIC. The wide change in pH with relative little change in alkalinity or DIC occurs mainly in "close system" carbonate evolution. In "closed system" carbonate evolution, the total carbon concentration is conserved (e.g., Langmuir, 1979).

The plot of alkalinity vs. Ca^{2+} (Fig. 8c) shows that for surface water, increase in alkalinity has a corresponding increase in Ca^{2+} to about 200 mg/l, and further increases in alkalinity is generally accompanied by decreases in Ca^{2+}. A similar behavior is observed for island groundwater which evolves mainly by evapo-concentration and shows a concomitant increase in alkalinity and Ca^{2+} followed by decreasing Ca^{2+} at an alkalinity concentration of greater than 200 mg/L. The same behavior for Ca^{2+} is exhibited by alkalinity vs. Mg^{2+} (Fig. 8e). We therefore suggest that this behavior in surface water and island groundwater is controlled by evapo-concentration coupled to reactions that remove Ca^{2+} and Mg^{2+} from surface water and island groundwater. This is characterized by the evolution of the cation facies from Mg-Ca to Ca-Na to Na+K with HCO_3 anion facies shown in Fig. 6. The precipitation of $CaCO_3$ leads to removal of equal molar proportions of Ca^{2+} and CO_3^{2-} from the solution which results in the relative enrichment in HCO_3^- and depletion in Ca^{2+} (Fig. 8c) (Eugster and Jones, 1979), because the molar ratio of Ca^{2+}: HCO_3^- is 1:2. The close correspondence in the behavior of Mg^{2+} and Ca^{2+} in the surface water and island groundwater strongly suggests that their evolution is affected by similar processes. Magnesium in the groundwater behaves similarly to Ca^{2+} which reflects the precipitation of magnesian calcite (McCarthy et al., 1991; 2012). For both shallow and deep groundwater, there is a much greater increase in Ca and Mg relative to alkalinity and DIC (Fig. 8c, d, e, and f). Conservation of total carbonate during close system carbonate evolution will result in increases in Ca and Mg with relatively minor increase in alkalinity or DIC (Langmuir et al., 1971; Fritz and Clark, 1997). The differences in carbonate evolution signifies an open system evolution for surface water and island groundwater in contrast to a closed system carbonate evolution for shallow and deep groundwater.

The continuous increase in Na^+ with increase in HCO_3^- (Fig. 8g) can be accounted for by weathering of Na bearing minerals (e.g., feldspars) which make up the mineralogy of the sediments in the Okavango Delta (Mazor et al., 1980; McCarthy and Metcalfe 1990; Huntsman-Mapila et al., 2005). The stoichiometry of the weathering reaction is such that there is a release of one equivalent of HCO_3^- for each Na^+ in the groundwater according to equation 2. The contribution of Na from the feldspar is reflected by the presence of quartz and kaolinite (Hunstman-Mapila et al., 2005).

Because much fewer samples were measured for DIC, the range in DIC concentrations does not cover that measured for alkalinity. Never the less, the behavior exhibited by alkalinity and Ca^{2+} at lower alkalinity concentrations (<200 mg/L) are similar to those for DIC vs. Ca^{2+} at concentration below 50 mg C/L for surface water (Fig. 8d). Even though it appears that the increases in Ca^{2+} concentrations are much greater than those for DIC, at DIC concentrations above 50 mg C/L, our data cannot be used to conclusively infer that Ca^{2+} decreases with increase in DIC concentrations for surface water as in the case of alkalinity. Data for alkalinity and Mg^{2+} (Fig. 8e) and DIC and Mg^{2+} (Fig. 8f) can be used to make arguments similar to those made for alkalinity and Ca^{2+} (Fig. 8c) and DIC and Ca^{2+} (Fig. 8d). The behavior of alkalinity relative to Na^+ (Fig. 8g) and DIC relative to Na^+ (Fig. 8h) are similar and show mostly positive relationships. The exceptions which are island groundwater samples show limited increase in Na^+ with much greater increase in alkalinity and DIC. We suspect that these may be cases where organic matter degradation (Mladenov et al., 2013) contributes to alkalinity and DIC. The difference in the chemical (alkalinity and DIC) evolution characterizing surface water and island groundwater and deep groundwater suggest lack of a genetic chemical connection. This difference can be understood as suggested by our model in Fig. 5 which shows that the Okavango River water is not a source of recharge to deep groundwater.

4.3 Carbon Cycling

To evaluate carbon cycling in groundwater, we examine shallow groundwater collected below the floodplain which we know is recharged by modern-day river water. In Fig. 2, the two shallow groundwater samples that plot with surface water samples are from depths of 25 cm below ground surface. We observe that shallow groundwater immediately assume DIC and $\delta^{13}C_{DIC}$ characteristics that are much different from surface water because by the time river water infiltrates to depths below 50 cm, the DIC concentration increases and the $\delta^{13}C_{DIC}$ becomes more negative (Fig. 2). We suggest that the increase in DIC is due to evaporation and equilibrium with atmospheric CO_2 and from microbial degradation of organic matter. The deep groundwater samples have DIC concentrations that are 5 to nearly 10 times greater than those of surface water. For river water that recharge the islands groundwater, the DIC is transformed in two different ways; the DIC concentrations and the $\delta^{13}C_{DIC}$ show significant increase for some locations and the DIC increases with decrease in the $\delta^{13}C_{DIC}$ for other locations (Fig. 2).

The results of the DIC concentrations and $\delta^{13}C_{DIC}$ of shallow and deep groundwater suggest that there must be addition of isotopically lighter carbon in groundwater after recharge from surface water. Organic matter degradation in the subsurface releases $CO_{2(g)}$ leading to an increased DIC concentrations and a decrease in the $\delta^{13}C_{DIC}$ composition. The $\delta^{13}C_{DIC}$ composition of the shallow and deep groundwater depends on the relative proportion of C3, CAM or C4 plants biomass respired in the sediments (Quade et al., 1989; Talbot, 1990). The organic matter in the sediments in the Okavango Delta and the Kalahari region can originate from C3 and C4 plants which have $\delta^{13}C$ of about -26.9‰ and -12.4‰, respectively (Ellery et al., 1992; Mladenov et al., 2005; 2007, Wang et al., 2007; 2010). While our results cannot be used to determine whether C3 or C4 vegetation is the organic matter respired in sediments to introduce carbon in to the groundwater, the $\delta^{13}C_{DIC}$ range from -8.2 to -11.8‰ which is lower than surface water in the distal portion of the Okavango Delta signifies a shift caused by $CO_{2(g)}$ from organic matter degradation. The $\delta^{13}C$

composition of the groundwater from the Kalahari region ranges from -4.8 to -13.3‰ (Mazor et al., 1974; Dincer et al., 1979; Bauer et al., 2006). Water directly recharged by the river water in the Shashe River valley has a δ13C of -4.8 to -7.8‰ (Bauer et al., 2006) suggesting that DIC recharged from river water can be traced in the groundwater system. We could suggest that the evapo-concentrated river water recharges and supplies carbon of an enriched $\delta^{13}C_{DIC}$ to the groundwater which is modified by carbon from biogenic degradation of organic matter with a lower $\delta^{13}C_{DIC}$ leading the observed increase in DIC and decrease in $\delta^{13}C_{DIC}$ for the shallow and deep groundwater. However, the lack of recharge of deep groundwater by modern day Okavango River (Fig. 5) suggests that carbon within the deep groundwater is older carbon. This DIC evolved in a closed system from $CO_{2\,(g)}$ from organic matter and carbonates in the aquifer. The isotopic composition of organic matter in sediment in and around the Okavango Delta ranges from -18 to -26‰ (Bird et al., 2004). The $\delta^{13}C$ of carbonates measured in sediments range from -1.5 to -6‰ (Kampunzu et al., 2007; Ringrose, 2009). Weathering carbonates of $\delta^{13}C$ of -1.5 to -6‰ in a closed carbonate evolution will produce DIC with $\delta^{13}C_{DIC}$ of -8 to -13‰ observed in deep groundwater. Despite the variable $\delta^{13}C$ for Kalahari groundwater, deep water samples in the Okavango region which are old water are characterized by $\delta^{13}C$ of -10 to -13‰ (Mazor et al., 1980). These groundwater samples are characterized by tritium of 0.9±0.2 TU and C-14 of < 60% modern carbon (Mazor et al., 1973). Although we show that modern day recharging river water can undergo DIC increase and $\delta^{13}C$ decrease, the DIC concentrations increase was about 2 times compared to the 5 to 10 times the DIC concentration increases in deep groundwater. We suggest that weathering of sodium feldspars will account for the relative increase of Na^+ and K^+ at the expense of Ca^{2+} and Mg^{2+} in deep groundwater (Fig. 6). But this fails to account for the excessively high DIC concentrations in the deep groundwater compared to the surface water. We further suggest that the evaporation of lake water during the fluvial period (>4000 Ka) could increase the HCO^{3-} cation (DIC) concentration in the surface water by evapo-concentration prior to aquifer recharge. We observe very high concentration in evaporated surface water such as the Magadikadi groundwater although the $\delta^{13}C_{DIC}$ is significantly enriched (-1.6±0.2‰) (Molwalefhe, 2003). This phenomenon will require excessive negative $\delta^{13}C_{DIC}$ in the soil or rocks to result in $\delta^{13}C_{DIC}$ of ~-11‰ for the deep groundwater (Fig. 2). Deep groundwater not recharged by modern day Okavango River is consistent with a unique chemical evolution (Fig. 6 and 8) and a unique source of carbon which is old.

CHAPTER V

CONCLUSIONS

Despite the difference in the potential source of the deep groundwater in the delta (river water) and deep groundwater out of the delta (rain water), they both have the same chemical evolution which is different from surface water, island groundwater and shallow groundwater. This suggests that both the deep groundwater in the delta and the deep groundwater out of the delta have a similar source (ancient pluvial) which is unrelated to the island groundwater and shallow groundwater source (modern day Okavango River).

The chemical characteristics and carbon isotopic compositions of dissolved inorganic carbon in shallow groundwater, surface water, island groundwater and deep groundwater was used to access the origin and dynamics of carbon in an inland deltaic system in southern Africa, Botswana. The carbon isotopic composition of DIC and chemical composition provide an assessment of the source of DIC in the Okavango Delta. Because deep groundwater has a chemical evolution which is not genetically related to modern day surface and shallow groundwater we suggest that the Okavango Delta has two DIC reservoirs: a modern day reservoir with recent carbon which is in river water, island groundwater and shallow groundwater and an ancient or old carbon reservoir which occurs in the deep groundwater. The modern day carbon reservoir is sourced from the present Okavango River while the deep carbon reservoir is sourced from ancient fluvial periods (> 0.8 ka) that occurred in the region. There are therefore two water circulation and cycling systems in the groundwater of the Okavango Delta; a shallow groundwater circulation system is recent and interacts with the surface water and a deep groundwater carbon systems which does not interact with the shallow groundwater system and acts mainly as a storage system.

CHAPTER VI

FUTURE WORK

Future analysis of the chemical and isotopic evolution of DIC in the groundwater of the Okavango Delta would be better defined if a chemical analysis of all the wells across the delta from shallow to deep groundwater with their absolute depths is carried out for all the geochemical parameters. This is important because during this study, we found that most of the chemical analyses done for some of the wells were incomplete. This will also make the dataset more valuable in understanding the temporal and spatial evolution of the groundwater.

In addition, age constraints of the sediments and groundwater in the Okavango Delta are essential in setting up the age records of the groundwater in relation to the present river water. This age constraints will compliment other groundwater age records in the region like: Mazor et al. (1977; 1980) and Bauer et al. (2006). Incorporating C-14 analysis of all the water types across the delta in to the geochemical analysis will further define the actual temporal relationship of the shallow groundwater and the deep groundwater. This will further define the temporal boundary between the two water circulation systems (transition or a sharp boundary). This will compliment other studies in the Kalahari region which have done C-14 age dating of groundwater; McCarthy et al. (1991; 2012) and Huntsman-Mapila et al. (2011). Studies on the age of the Okavango Delta in relation to the existence of the Lake Makgadikgadi will be important in investigating the spatial and temporal distribution of surface water that influenced the groundwater.

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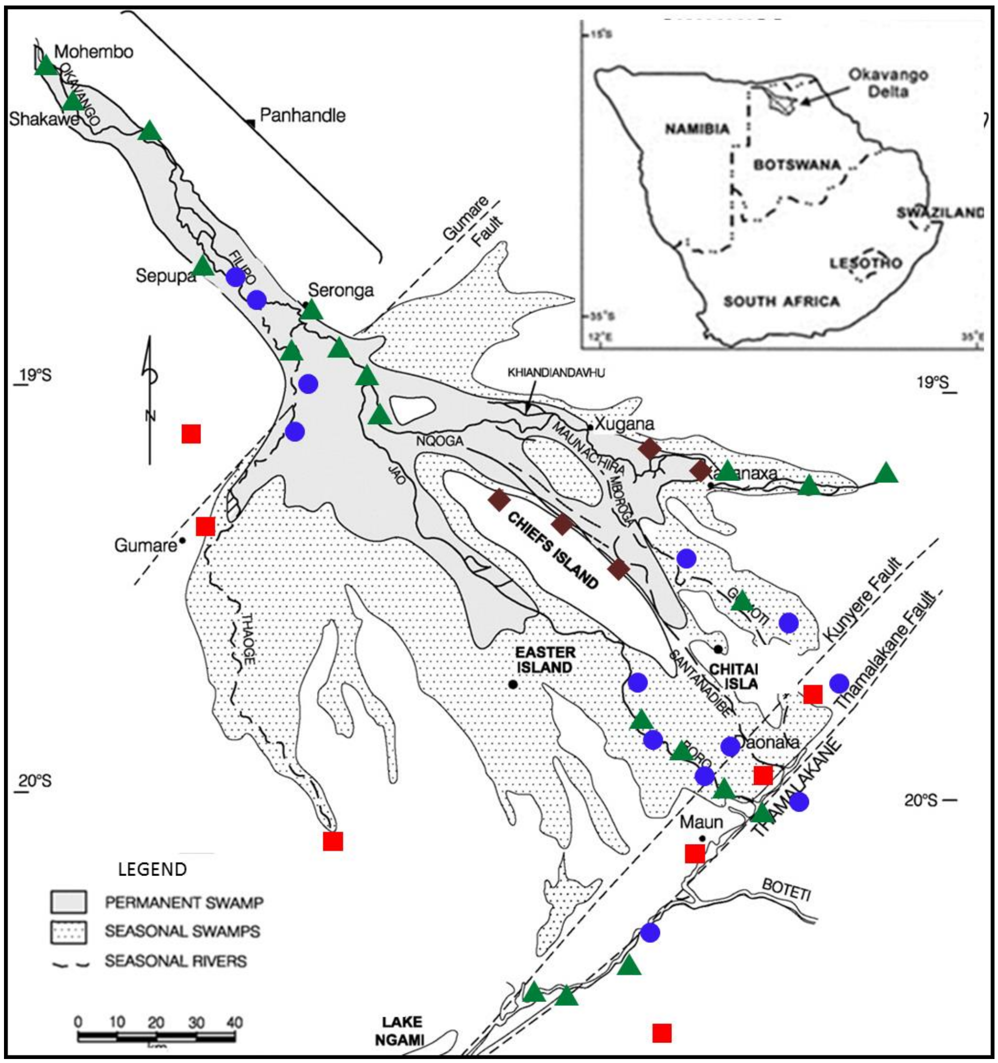

Fig. 1. Map of Okavango Delta, Botswana, showing representaive sample locations (filled circles are shallow groundwater, filled squares are deep groundwater, filled diamonds are island groundwater and filled triangles are surface water sampling points). Map is modified from McCarthy et al. (2012).

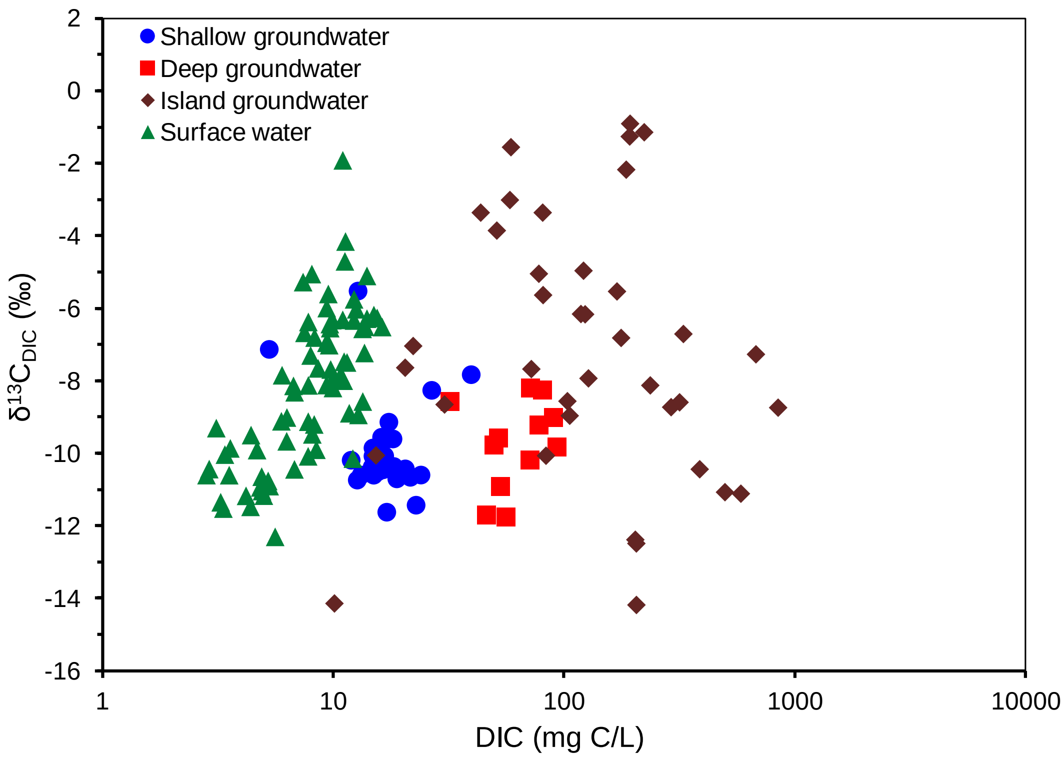

Fig. 2. Plot of dissolved inorganic carbon (DIC) vs. the stable carbon isotope composition of DIC ($\delta^{13}C_{DIC}$) for shallow groundwater, deep groundwater, island groundwater and surface water.

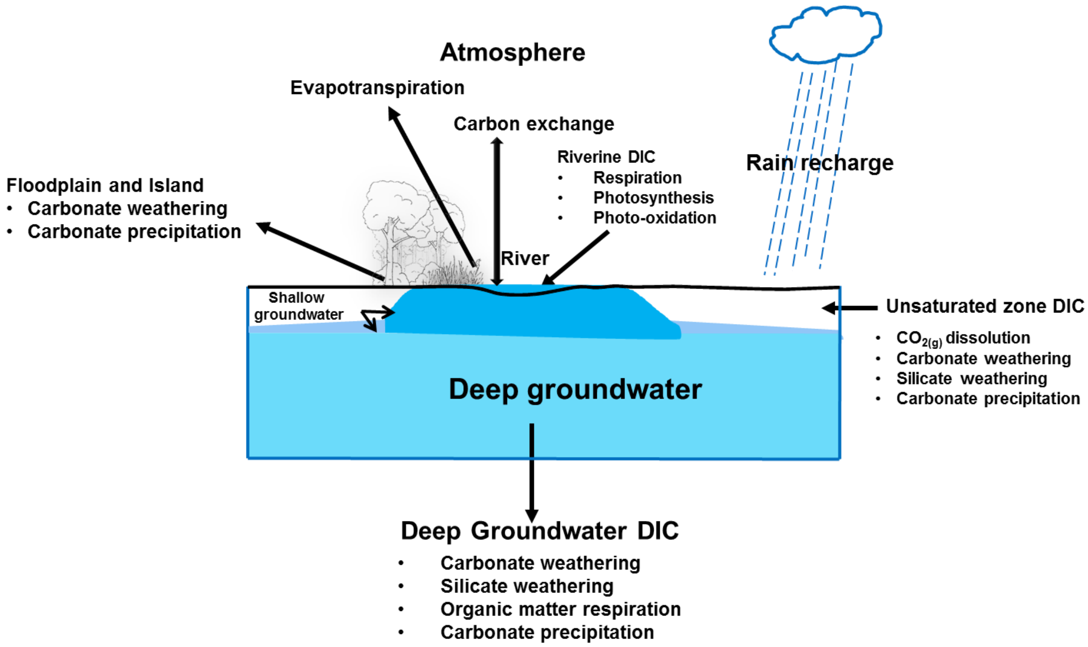

Fig. 3. Conceptual model showing the pathways (riverine vs. soil zone) and processes that affect dissolved inorganic carbon (DIC) in the river and soil zone prior to recharge of groundwater in the Okavango Delta Botswana.

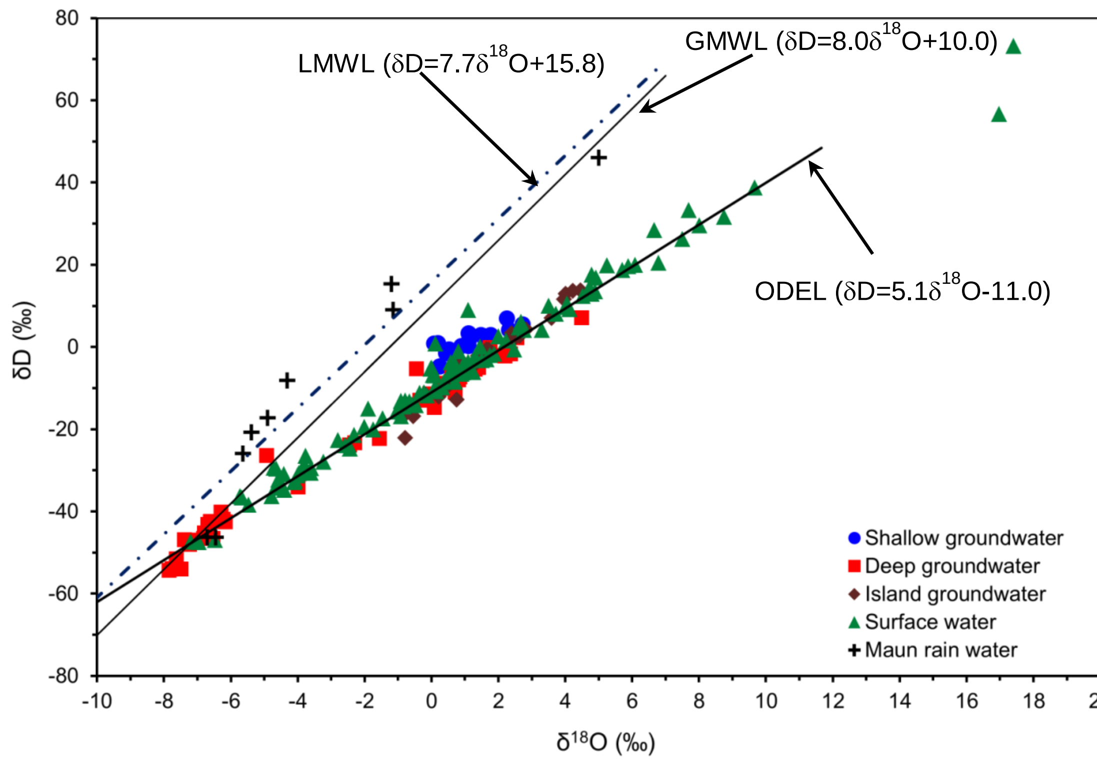

Fig. 4: Plot of the stable oxygen isotopic composition ($\delta^{18}O$) vs. stable hydrogen isotope (δD) for shallow groundwater, deep groundwater, island groundwater and surface water. Also shown is the local meteoric water line (LMWL) constructed from Maun rain collected in 2011-2012, the global meteoric water line (GMWL; Craig and Gordon, 1965) and Okavango Delta evaporation line (ODEL; Dincer et al., 1979)

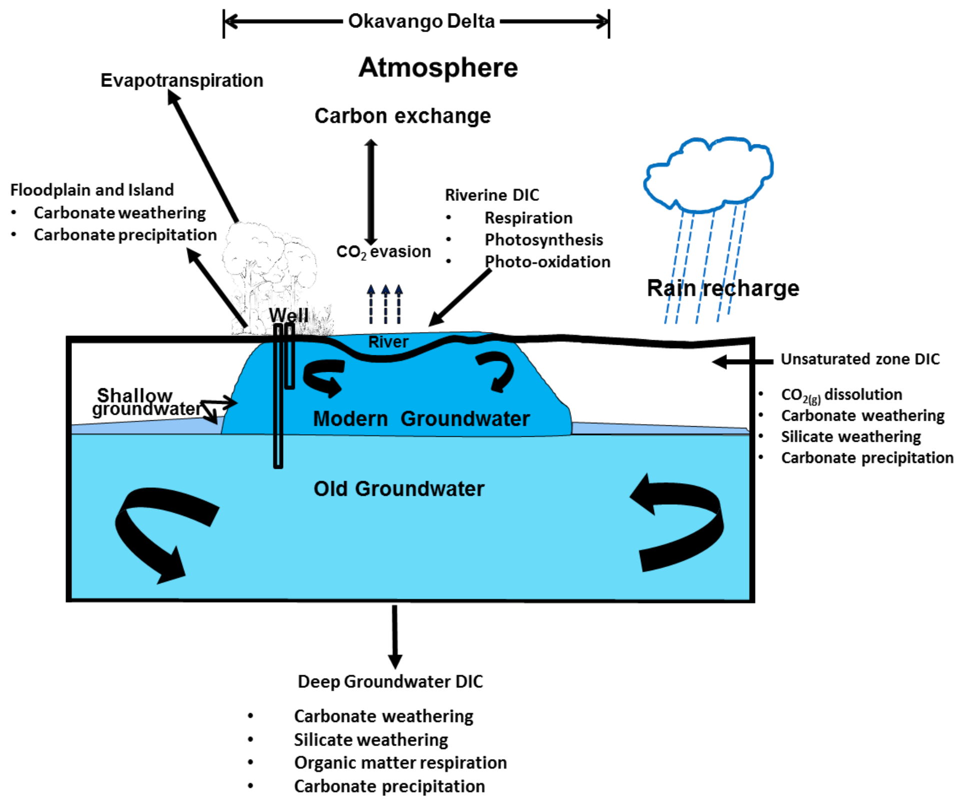

Fig. 5. Conceptual model showing groundwater recharge pattern in the Okavango Delta and the processes that affect DIC.

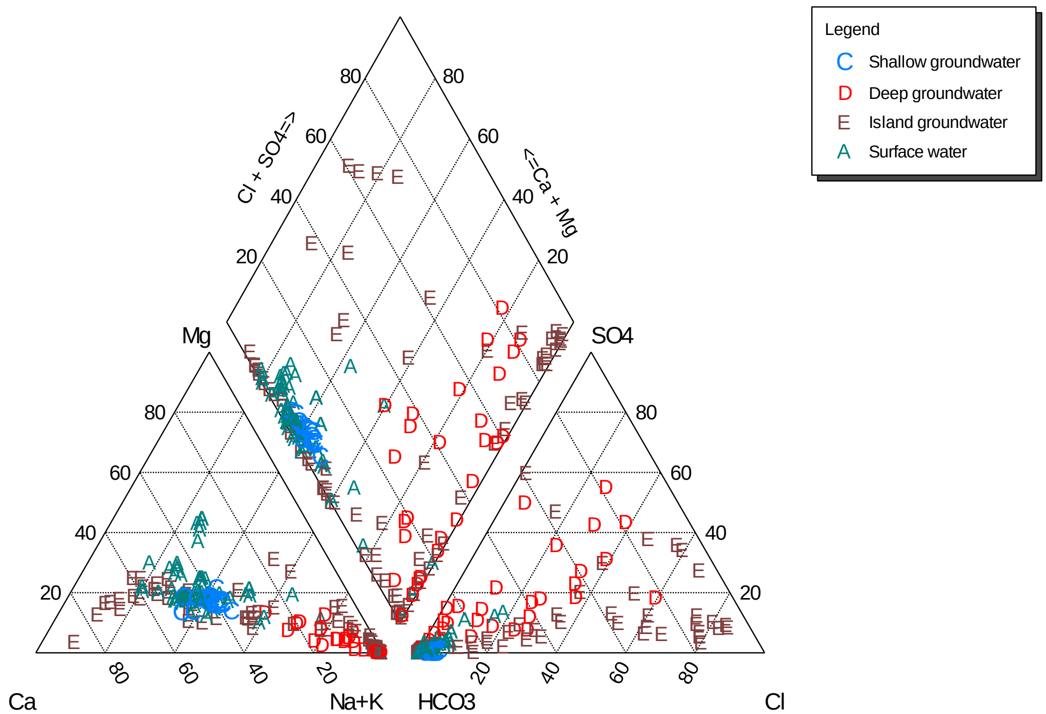

Fig. 6. Piper plot for shallow groundwater, deep groundwater, island groundwater and surface water

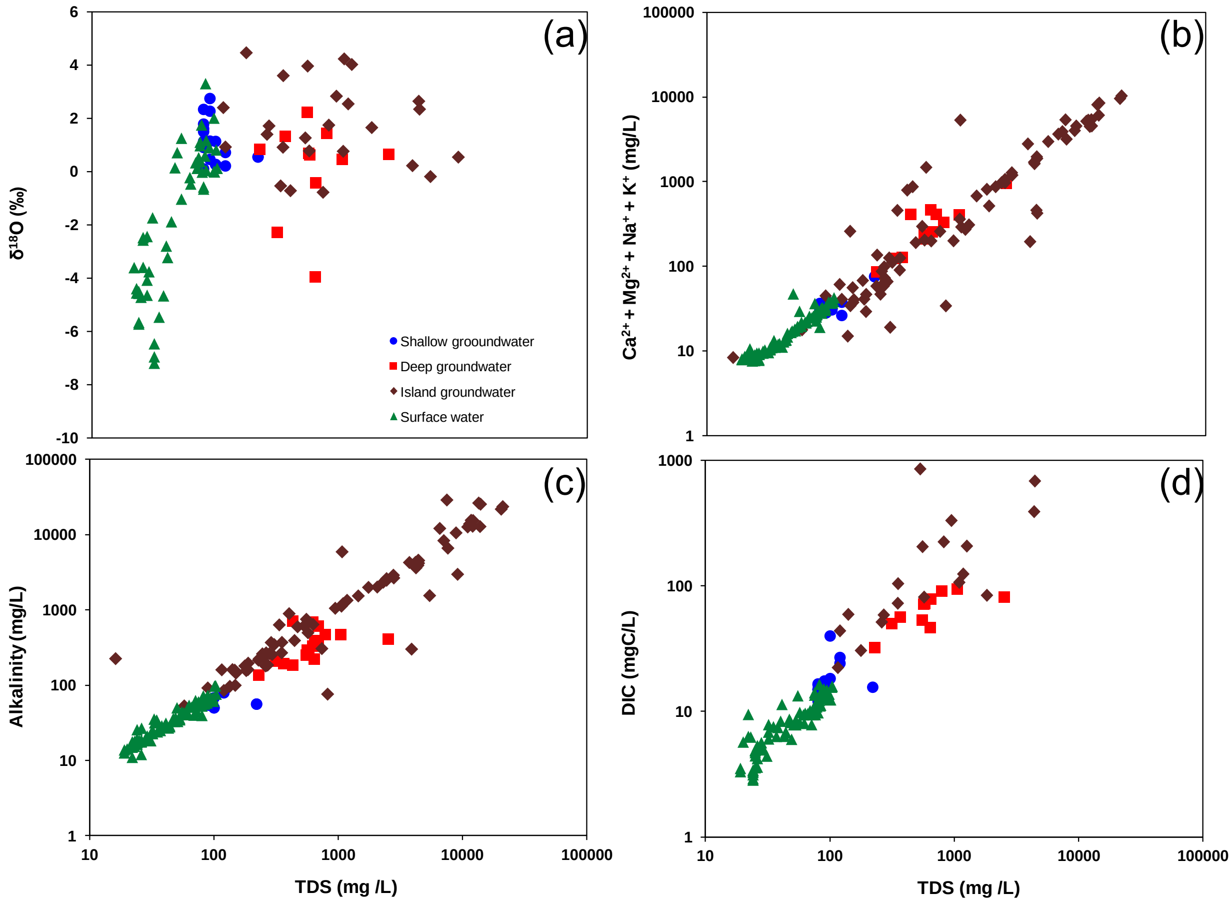

Fig. 7. Cross plots of total dissolved solids (TDS) vs. stable isotopic composition of oxygen ($\delta^{18}O$) (a), TDS vs. total cations (Ca^{2+} + Mg^{2+} + K^{+} + Na^{+}) (b), TDS vs. alkalinity (c), TDS vs. dissolved inorganic carbon (DIC) (d) for shallow groundwater, deep groundwater, island groundwater and surface water.

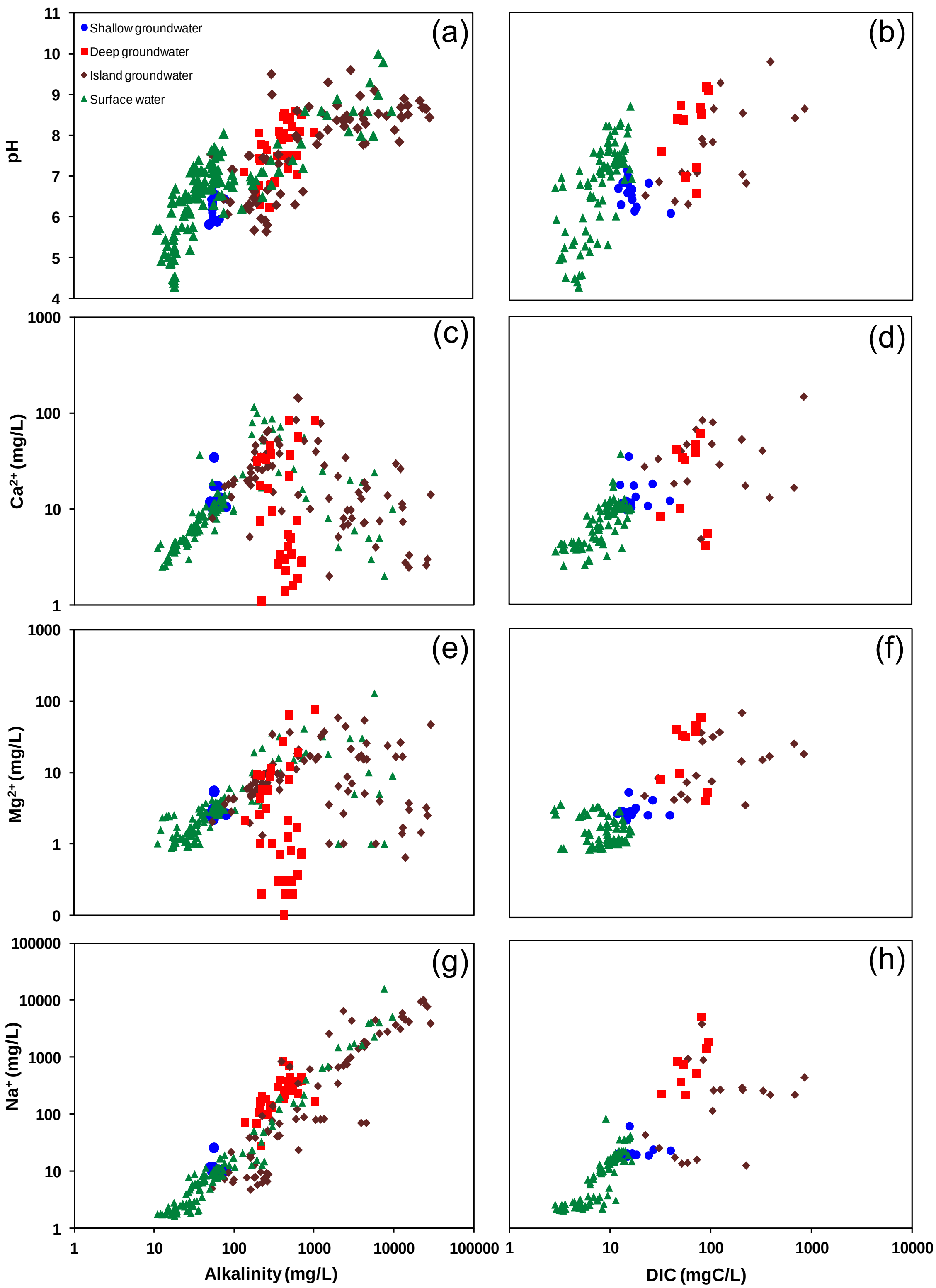

Fig. 8. Cross plots of alkalinity vs. pH (a), dissolved inorganic carbon (DIC) vs. pH (b), alkalinity vs. Ca^{2+} (c), DIC vs. Ca^{2+} (d), alkalinity vs. Mg^{2+} (e), DIC vs. Mg^{2+} (f), alkalinity vs. Na^{+} (g), DIC vs. Na^{+} (h), for shallow groundwater, deep groundwater, island groundwater and surface water.

Table 1. Descriptive statistics for the physical, chemical and isotopic parameters for shallow groundwater, deep groundwater, island groundwater and surface water

Parameter	Water type	Minimum	Maximum	Mean	Standard deviation	Number of samples
TDS (mg/l)	Shallow groundwater	80	220	104	43	19
	Deep groundwater	176	5640	988	1139	27
	Island groundwater	120	2446	3220	4940	51
	Surface water	19	104	53	27	87
EC (mS/cm)	Shallow groundwater	123	334	159	64	19
	Deep groundwater	200	3917	1126	1103	18
	Island groundwater	24	31400	4996	7149	81
	Surface water	0	5500	119	505	133
$\delta^{18}O$ (‰)	Shallow groundwater	0.1	2.7	1.1	0.8	19
	Deep groundwater	-7.8	4.5	-2.6	3.9	43
	Island groundwater	-0.8	4.5	1.7	1.5	26
	Surface water	-7.2	17.4	0.5	4.4	104
δD (‰)	Shallow groundwater	-5	7	1	3	19
	Deep groundwater	-9	2	-25	20	42
	Island groundwater	-22	14	-2	10	25
	Surface water	-47	73	-7	22	104
Na (mg/l)	Shallow groundwater	9.9	25.9	12.3	4.8	19
	Deep groundwater	28.0	851.7	273.9	175.2	34
	Island groundwater	4.8	10209.1	1461.8	2395.4	81
	Surface water	1.7	115000.0	1172.0	9884.9	138
Ca (mg/l)	Shallow groundwater	9.6	34.4	14.5	7.5	19
	Deep groundwater	0.6	84.5	20.1	23.7	34
	Island groundwater	2.0	145.1	24.9	26.8	38

	Surface water	1.0	116.0	14.6	20.7	138
Mg (mg/l)	Shallow groundwater	2.2	5.4	3.1	0.9	19
	Deep groundwater	0.1	75.8	8.2	16.7	34
	Island groundwater	0.6	68.8	12.7	14.0	81
	Surface water	0.9	128.0	6.4	15.1	138
K (mg/l)	Shallow groundwater	3.1	9.9	5.8	2.2	19
	Deep groundwater	2.0	48.0	12.0	8.8	34
	Island groundwater	0.8	1365.0	167.6	257.5	81
	Surface water	1.0	8700.0	115.7	763.6	137
Alkalinity (mg/l)	Shallow groundwater	50	79	57	7	18
	Deep groundwater	137	1026	405	185	38
	Island groundwater	3	28825	3675	6756	78
	Surface water	11	9605	526	1561	135
DIC (mg C/L)	Shallow groundwater	5.3	39.6	17.6	5.8	32
	Deep groundwater	32.0	93.2	65.6	19.5	11
	Island groundwater	10.1	847.5	198.2	209.0	30
	Surface water	0.6	16.3	8.2	3.8	77
$\delta^{13}C_{DIC}$ (‰)	Shallow groundwater	-10.7	-3.9	-9.6	1.7	17
	Deep groundwater	-11.7	-8.3	-9.8	1.2	17
	Island groundwater	-14.2	-1.6	-8.0	3.4	30
	Surface water	-12.3	-1.9	-8.3	2.1	86
pH	Shallow groundwater	5.8	6.7	6.2	0.3	18
	Deep groundwater	6.2	8.6	7.6	0.7	39
	Island groundwater	5.6	9.6	7.6	1.2	80
	Surface water	4.3	10.0	6.7	0.8	97
Sulfate (mg/l)	Shallow groundwater	0.1	3.6	0.7	1.1	19
	Deep groundwater	4.6	1162.0	150.8	241.0	38
	Island groundwater	0.1	606.5	64.7	146.3	35

	Surface water	0.0	1700.0	25.9	173.1	92
Cl (mg/l)	Shallow groundwater	1.4	2.5	1.9	0.3	19
	Deep groundwater	1.2	1596.7	135.5	271.1	38
	Island groundwater	0.2	830.0	81.3	147.2	69
	Surface water	0.1	6400.0	90.7	651.1	112

APPENDICES

Table S1. Chemical and isotopic data for deep groundwater, shallow groundwater and island groundwater in the Okavango Delta

Sample station	Long	Lat	Date	pH	Temp	Cond	DO	Ca	Mg	Na	K	Fe	Alk	Cl	SO_4^{2-}	$\delta^{18}O$	δD	TDS	$\delta^{13}C_{DIC}$	DIC
Dincer et al. (1979)																				
Kondo	–	–	6/9/75	–	–	–	–	–	–	–	–	–	–	–	–	-	-	-	–	–
Kondo	–	–	2/9/75	–	–	–	–	–	–	–	–	–	–	–	–	0.0	-11.5	320	–	–
Kodmotswana	–	–	3/9/75	–	–	–	–	–	–	–	–	–	–	–	–	0.1	-14.8	-	–	–
Gumare	–	–	6/9/75	–	–	–	–	–	–	–	–	–	–	–	–	0.7	-11.1	1676	–	–
Tsau	–	–	3/9/75	–	–	–	–	–	–	–	–	–	–	–	–	-2.4	-23.9	176	–	–
Nokaneng	–	–	20/09/75	–	–	–	–	–	–	–	–	–	–	–	–	-1.5	-22.4	412	–	–
TFC Barrier (borehole)	–	–	20/09/75	–	–	–	–	–	–	–	–	–	–	–	–	-2.8	-27.4		–	–
Maun Borehole	–	–	3/11/75	–	–	–	–	–	–	–	–	–	–	–	–	2.4	-1.8	320	–	–
Mabe I (Haina Velt)	–	–	26/11/75	–	–	–	–	–	–	–	–	–	–	–	–	4.5	7.0	–	–	–
Mabe II (Haina Velt)	–	–	26/11/75	–	–	–	–	–	–	–	–	–	–	–	–	-7.6	-51.6	–	–	–
Haina velt 5001	–	–	7/4/76	–	–	–	–	–	–	–	–	–	–	–	–	-6.2	-42.0	–	–	–
Haina velt 5004	–	–	8/4/76	–	–	–	–	–	–	–	–	–	–	–	–	-6.5	-46.7	–	–	–
Haina velt 5008	–	–	8/4/76	–	–	–	–	–	–	–	–	–	–	–	–	-6.8	-	–	–	–
Haina velt 5010	–	–	9/4/76	–	–	–	–	–	–	–	–	–	–	–	–	-6.8	-46.7	–	–	–
Haina velt 5012	–	–	9/4/76	–	–	–	–	–	–	–	–	–	–	–	–	-7.2	-48.1	–	–	–
Haina velt 5013	–	–	9/4/76	–	–	–	–	–	–	–	–	–	–	–	–	-6.2	-42.6	2210	–	–
Haina velt 5022	–	–	10/4/76	–	–	–	–	–	–	–	–	–	–	–	–	-6.8	-45.3	–	–	–
Haina velt 5026	–	–	13/04/76	–	–	–	–	–	–	–	–	–	–	–	–	-6.6	-44.4	5640	–	–
Haina velt 5028	–	–	13/04/76	–	–	–	–	–	–	–	–	–	–	–	–	-7.2	-47.1	–	–	–

Haina velt 5031	–	–	13/04/78	–	–	–	–	–	–	–	–	–	–	–	–	-6.6	-42.5	–	–	–
Haina velt 5032	–	–	14/04/76	–	–	–	–	–	–	–	–	–	–	–	–	-6.3	-40.3	–	–	–
Machaha (L Ngami) 5200	–	–	18/04/76	–	–	–	–	–	–	–	–	–	–	–	–	-6.7	-43.3	–	–	–
Xhabaxwa (L. Ngami) 5213	–	–	19/05/76	–	–	–	–	–	–	–	–	–	–	–	–	0.4	-10.2	–	–	–
Motopi pan (L.Ngami) 5222	–	–	20/05/76	–	–	–	–	–	–	–	–	–	–	–	–	0.9	-7.4	–	–	–
Maigo (L. Ngami) 5228	–	–	20/05/76	–	–	–	–	–	–	–	–	–	–	–	–	-4.9	-26.5	–	–	–
Hitoto (L. Ngami) 5239	–	–	21/05/76	–	–	–	–	–	–	–	–	–	–	–	–	-7.4	-47.0	–	–	–
Masalanyane (L. Ngami) 5262	–	–	21/05/76	–	–	–	–	–	–	–	–	–	–	–	–	-7.5	-54.1	–	–	–
Matlabologa (L. Ngami 5263)	–	–		–	–	–	–	–	–	–	–	–	–	–	–	-7.8	-54.4	–	–	–
Kara (L. Ngami) 5269	–	–		–	–	–	–	–	–	–	–	–	–	–	–	-7.7	-54.0	–	–	–
Patane I (L. Ngami) 5255	–	–		–	–	–	–	–	–	–	–	–	–	–	–	-0.3	-13.1	–	–	–
Atekwana, (2011) unpublished																				
BH 10042	023°06.108'E	20°10.718'S	22/07/11	6.2	24.1	886	3.1	45.8	8.80	143.6	18.1	91.2	284.0	70.7	43.9	0.6	-7.2	-12	-8.2	71.7
BH 10046	023°05.865'E	20°11.095'S	22/07/11	6.8	24.3	868	2.2	37.6	11.19	140.1	21.6	96.9	291.0	73.4	27.2	0.7	-7.3	-15	-10.2	71.1
BH 10096	023°05.619'E	20°11.445'S	23/07/11	6.6	24.0	561	2.2	31.7	9.36	70.2	16.2	100.9	192.0	39.8	16.8	1.3	-5.5	-11	-11.8	56.0
BH 7188	–	–	23/07/11	8.4	24.7	1314	1.3	5.4	2.12	387.5	13.1	80.3	471.0	131.0	120.0	0.5	-8.9	-24	-9.8	93.2
BH 7190	023°22.679'E	20°00.073'S	23/07/11	8.5	24.7	1210	2.7	4.1	1.24	313.1	12.2	93.0	469.0	41.7	72.2	1.4	-5.1	-22	-9.0	90.1
BH 7961	023°23.168'E	19°57.806'S	23/07/11	8.0	24.3	991	6.0					84.4	393.0	29.1	67.5	-0.4	-5.4	-27	-9.2	77.8
BH 8351	023°31.560'E	19°53.441S	23/07/11	7.8	25.0	846	3.4	33.5	3.13	186.8	13.7	91.2	252.0	61.6	56.9	2.2	-2.4	-2	-10.9	53.0
BH 8569	022°18.361'E	19°06.478S	25/07/11	7.1	25.3	351	0.4	8.2	2.12	72.6	3.6	51.7	137.0	4.1	20.8	0.8	-8.1	7	-8.6	32.0
BH 8606	022°18.624'E	19°06.393S	25/07/11	7.8	25.8	982	0.4	40.7	5.61	203.8	6.8	56.2	223.0	17.9	198.5	-4.0	-34.2	-52	-11.7	46.2
BH 8607	022°18.820'E	19°06.273S	25/07/11	8.1	25.0	484	4.6	9.9	2.55	106.6	5.4	58.6	208.0	1.6	28.8	-2.3	-23.4	-42	-9.8	49.8
BH 8786	023°56.952'E	19°56.952S	25/07/11	7.9	24.2	3917	2.8	60.1	27.16	851.7	19.9	74.8	409.0	498.4	762.6	0.6	-7.3	-47	-8.3	80.5
Huntsman-Mapila et al. (2006)																				
SHM01	–	–	10/3/03	7.9	29.8	-	4.9	36.6	12.1	440.0	14.0	0.1	503.0	380.1	411.5	–	–	-47	–	–
SHM02	–	–	10/17/03	8.5	27.6	-	2.4	5	0.8	390.0	15.0		516.0	158.4	345.7	–	–	-48	–	–
SHM03	–	–	11/30/03	7.2	26.6	-	2.5	22	8	350.0	14.0		488.0	224.5	203.9	–	–	-43	–	–

SHM04	–	–	11/30/03	7.2	27.0	-	3.0	84.5	63.3	720.0	20.0		486.0	419.0	1162.0	–	–	-45	–	–
MAM05	22°51'54.74"E	19°39'01.49"S	8/12/03	7.5	27.3	-	1.9	0.6	0.1	190.0	4.0	0.9	417.0	1.2	4.6	–	–	-44	–	–
MAM06	22°52'54.69"E	19°40'44.45"S	6/1/03	8.2	26.9	-	2.0	–	–	–	–	–	–	–	–	–	–	-47	–	–
MAM07	–	–	6/16/03	8.5	27.2	-	2.0	3	0.3	270.0	9.0	1.2	425.0	11.0	38.0	–	–	-43	–	–
KUM08	22°50'07.95"E	19°42'13.18"S	8/19/03	8.1	26.1	-	2.9	1.4	0.3	230.0	9.0	1.1	430.0	4.5	24.2	–	–	-40	–	–
KUM09	–	–	6/23/03	8.1	25.7	-	2.1	83.6	75.8	168.0	48.0		1026.0	1596.7	666.4	–	–	-43	–	–
KUM10	–	–	6/19/03	8.5	25.1	-	2.0	2.3	0.2	220.0	5.0	1.5	437.0	9.9	31.3	–	–	-10	–	–
KUM11	–	–	7/3/03	8.2	24.8	-	1.5	1.6	0.2	310.0	6.0	0.4	543.0	56.9	138.8	–	–	-7	–	–
KUM12	–	–	6/27/03	7.6	23.9	-	1.9	16.3	5.7	100.0	10.0	0.7	264.0	165.3	318.8	–	–	-27	–	–
KUM13	–	–	8/29/03	7.0	24.7		1.8	56.6	19.1	230.0	30.0		632.0	85.9	59.4	–	–	-47	–	–
KUM14	–	–	7/3/03	7.4	24.4	-	2.4	17.7	4.4	150.0	10.0	0.3	212.0	19.4	11.0	–	–	-54	–	–
KUM15	–	–	9/3/03	6.8	26.5	-	1.7	7.5	1	170.0	10.0	0.4	210.0	98.6	67.7	–	–	-54	–	–
GOM16	19°13'22.21"E	23°33'07.93"S	11/4/03	6.3	33.8	-	0.8	33.9	9	28.0	8.0	13.2	217.0	2.4	19.1	–	–	-54	–	–
GOM17	–	–	11/20/03	7.5	28.3	-	1.2	2.7	0.3	300.0	3.0		353.0	175.7	191.6	–	–	-13	–	–
GOM18	–	–	11/12/03	7.4	29.5	-	1.0	1.1	0.2	170.0	2.0	1.3	219.0	19.8	24.2	–	–		–	–
GOM19	–	–	11/12/03	7.5	27.9	-	1.6	3.4	0.3	260.0	10.0	1.8	518.0	7.9	50.1	–	–	-7	–	–
GOM20	–	–	11/30/03	6.8	26.7	-	1.6	9.5	1	130.0	12.0		297.0	2.5	10.5	–	–	-7	–	–
9830a	23°45'02.97"E	19°47'31.57"S	2/15/03	8.1	25.3	-	-	2.8	0.7	454.0	6.6	0.1	693.0	137.0	94.0	–	–	-6	-9.4	–
9834a	–	–	8/27/02	8.5	24.3	-	-	2.9	0.8	392.0	14.0	0.2	711.0	80.0	50.0	–	–	-9	-11.0	–
9837a	–	–	9/2/02	8.6	25.4	-	1.7	7.6	1.7	390.0	9.3	0.2	607.0	139.0	73.0	–	–	-5	-8.9	–
9904a	–	–	12/18/02	7.5	26.5	-	1.3	1.9	0.4	370.0	5.2	0.1	624.0	64.0	85.0	–	–	-5	–	–
9906a	–	–	1/26/03	8.1	28.0	-	3.5	3.3	0.7	404.0	4.2	0.8	375.0	238.0	196.0	–	–	-2	–	–
Atekwana, (2011) unpublished																				
Maun Well field Borehole 46	23.09774E	20.18496S	–	6.9	25.4	-	17.1	–	–	–	–	–	328.0	28.7	8.7	–	–	-34	-9.4	–
Maun Well field Borehole 44	23.08586E	20.1786S	–	6.7	25.0	-	2.3	–	–	–	–	–	186.0	19.2	10.0	–	–	-23	-11.0	–
Maun Well field Borehole 42	23.10171E	20.17855S	–	6.9	25.0	-	2.2	–	–	–	–	–	332.0	33.0	21.1	–	–	-7	-8.9	–
Thamalakane@ Toteng Bridge	–	–	–	6.7	14.5	137	5.9	11.9	2.8	10.7	6.5	–	54.9	2.1	0.4	0.4	-1.6	–	-10.6	14.7

Thamalakane@ Toteng Bridge	–	–	–	6.3	13.3	128	5.0	10.1	2.7	10.7	5.7	–	55.9	1.8	0.2	1.1	0.2	–	-10.2	12.0
Thamalakane@ Toteng Bridge	–	–	–	6.5	14.4	130	5.9	11.3	3.0	10.2	5.5	–	57.2	1.8	0.4	2.7	5.4	–	-10.6	13.2
Thamalakane@ Toteng Bridge	–	–	–	6.6	15.4	129	3.4	10.6	2.8	10.2	5.8	–	57.4	1.8	0.3	2.3	4.1	–	-10.1	14.9
Thamalakane@ Toteng Bridge	–	–	–	6.0	16.1	124	5.3	17.4	2.8	10.4	5.9	–	55.4	1.6	0.1	0.1	0.8	–	-10.7	12.7
Thamalakane@ Toteng Bridge	–	–	–	6.4	16.9	123	3.0	10.2	2.5	9.9	5.6	–	53.3	1.4	0.1	0.9	0.1	–	-9.9	14.9
Thamalakane@ Toteng Bridge	–	–	–	6.2	17.7	127	1.7	9.6	2.2	10.1	8.1	–	54.8	1.6	0.1	1.6	2.5	–	-10.4	14.7
Thamalakane@ Toteng Bridge	–	–	–	6.1	18.2	128	1.5	10.1	2.6	10.7	5.7	–	54.9	1.7	0.1	1.1	1.3	–	-10.5	16.4
Thamalakane@ Toteng Bridge	–	–	–	6.3	18.6	130	1.5	11.3	3.0	10.4	3.6	–	54.3	1.7	0.1	1.1	3.2	–	-9.7	16.4
Thamalakane@ Toteng Bridge	–	–	–	6.2	19.0	130	1.3	11.2	2.8	10.3	3.5	–	55.5	1.6	0.1	1.5	2.9	–	-9.6	16.2
Thamalakane@ Toteng Bridge	–	–	–	6.2	18.8	130	8.8	10.6	3.0	12.1	3.8	–	54.5	1.9	0.1	1.8	2.9	–	–	–
Thamalakane@ Toteng Bridge	–	–	–	5.9	19.8	134	5.3	17.2	3.0	10.3	9.7	–	63.2	1.7	0.1	2.3	6.9	–	-9.6	17.4
Thamalakane@ Toteng Bridge	–	–	–	5.9	20.3	151	2.4	13.1	3.3	10.4	3.9	–	67.8	1.7	0.1	1.1	3.3	–	-9.6	18.2
Thamalakane@ Toteng Bridge	–	–	–	-	19.9	189	4.7	17.8	4.2	12.2	3.5	–	-	1.9	0.1	0.2	0.9	–	-8.3	26.7
Sedia Riverside hotel	–	–	–	5.8	22.4	148	3.6	11.9	2.6	11.8	5.2	–	50.0	2.2	1.6	0.3	-4.7	–	-7.8	39.6
Sedia Riverside hotel	–	–	–	6.3	20.0	334	2.7	34.5	5.4	25.9	9.9	–	56.0	2.5	3.6	0.5	-0.6	–	–	–
Sedia Riverside hotel	–	–	–	5.8	22.4	148	3.6	11.9	2.6	11.8	5.2	–	50.0	2.2	1.6	0.3	-4.7	–	–	–
The beach 3m	–	–	–	6.4	20.7	178	0.7	10.5	2.6	10.2	3.1	–	79.1	2.5	0.2	0.7	-1.8	–	-10.6	24.0
Sedia Riverside hotel	–	–	–	6.3	20.0	334	2.7	34.5	5.4	25.9	9.9	–	56.0	2.5	3.6	0.5	-0.6	–	-3.9	15.5
Island water																				
McCarthy et al. (1991)																				
Pit A	–	–	–	9.5	-	9500	-	4	1	4500.0	825.0	-	-	830.0	211.0	0.8	-12.8	–	–	–
Pit C	–	–	–	9.1	-	1600	-	10	17	620.0	148.0	-	-	12.0	5.0	-0.7	-15.9	–	–	–
Pit E	–	–	–	8.7	-	600	-	15	13	140.0	91.0	-	-	5.0	5.0	-0.8	-22.1	–	–	–
Pit F	–	–	–	9.0	-	1100	-	14	17	350.0	77.0	-	-	8.0	5.0	-0.6	-16.8	–	–	–
Pit H	–	–	–	8.6	-	500	-	28	34	78.0	56.0	-	-	5.0	5.0	0.2	-12.0	–	–	–
Pit I	–	–	–	9.5	-	5800	-	2	1	2600.0	375.0	-	-	157.0	50.0	-0.2	-11.4	–	–	–
Pit K	–	–	–	9.3		8100	-	8	7	4400.0	129.0	-	-	220.0	50.0	0.5	-9.0	–	–	–
Pit L	–	–	–	9.6	-	13600	-	8	1	6500.0	172.0	-	-	440.0	50.0	1.1		–	–	–

Atekwana, (2011) unpublished																				
C5	–	–	7/12-13/11	6.7	19.2	539	5.8	65.8	9.2	8.9	6.6	-	269.0	3.4	0.1	0.9	-3.9	-2	-7.7	72.2
C5	–	–	7/12-13/11	6.7	20.7	394	5.3	39.3	5.1	7.8	6.4	-	180.0	1.5	0.2	1.4	-2.1	0	-3.9	51.2
C5	–	–	7/12-13/11	6.6	21.5	411	6.1	46.1	7.4	8.0	7.5	-	185.0	1.4	0.1	1.7	-0.5	5	-3.0	58.3
C6	–	–	7/12-13/11	-	-	-	-	19.0	4.3	224.7	11.8	-	–	–	–	–	–	4	–	–
C6	–	–	7/12-13/11	6.0	22.4	211	1.2	18.0	4.3	9.5	9.1	-	85.0	1.7	0.2	0.9	-3.6	1	-1.6	58.9
C6	–	–	7/12-13/11	6.1	21.8	185	1.7	17.1	3.6	7.4	6.2	-	76.0	1.4	0.3	1.7	-2.4	0	-3.4	43.6
C7	23 10 39.1E	19 325 0.8S	7/12-13/11	6.4	23.4	1262	1.8	145.1	18.4	123.8	9.4	-	614.0	12.8	0.1	1.3	-4.5	3	-13.1	222.7
C10	–	–	7/12-13/11	8.0	20.2	815	1.2	4.8	36.4	685.4	749.6	-	497.0	67.8	23.4	0.8	-5.2	1	-8.7	847.5
C9	–	–	7/12-13/11	7.4	17.7	882	7.5	-	-	-	-	-	-	-	-	–	–	3	-3.4	80.9
Bauer-Gottwein et al. (2007)																				
C1D	–	–	–	6.2	26.3	224	1.54	19.7	5.9	7.8	7.1	2.3	144.7	1.7	0.2	–	–	3	–	–
C1R	–	–	–	5.6	26.3	366	0.24	27.4	7.2	6.7	5.7	3.0	260.5	1.3	0.3	–	–	7	–	–
C2D	–	–	–	6.3	24.4	219	1.7	20.4	5.8	18.3	11.6	0.5	158.2	1.2		–	–	3	–	–
C2R	–	–	–	5.8	24.4	392	0.47	27.7	6.3	49.7	15.0	1.8	268.5	1.7	0.4	–	–	1	–	–
C3D	–	–	–	6.4	24.0	281	2.65	26.5	6.1	5.8	8.4	2.5	196.0	1.6	0.2	–	–	-5	–	–
C3R	–	–	–	5.9	24.0	383	383	37.9	9.6	7.9	6.4	1.3	251.6	1.4	0.7	–	–	-1	–	–
C4D	–	–	–	6.3	23.8	210	210	17.7	4.6	4.8	7.3	1.0	161.0	1.3	0.1	–	–	-5	–	–
C4R	–	–	–	5.7	23.8	396	396	20.9	5.4	39.1	7.6	3.4	183.8	0.7	0.2	–	–	-2	–	–
C5D	–	–	–	6.4	23.7	340	340	35.0	6.3	9.8	7.4	1.2	215.0	0.7	0.8	–	–	-1	–	–
C5R	–	–	–	6.3	23.7	455	455	52.2	9.6	41.1	8.8	0.1	346.4	0.6	0.3	–	–	–	–	–
C6D	–	–	–	6.4	24.5	133	133	13.3	2.8	21.8	7.0	0.9	91.8	0.2	0.1	–	–	–	–	–
C6R	–	–	–	6.0	24.5	344	344	25.5	7.2	93.9	9.5	0.4	224.0	6.3	2.1	–	–	-13	–	–
C7D	–	–	–	6.6	25.0	663	663	9.5	9.2	845.8	7.6	1.1	391.6	0.6		–	–	-16	–	–
C7R	–	–	–	6.3	25.0	702	702	84.6	11.1	82.8	12.4	8.2	596.4	0.4	0.2	–	–	-22	–	–
C8D	–	–	–	7.8	28.9	5569	5569	18.9	53.9	1894.8	825.5	0.0	4262.0	63.4	51.8	–	–	-17	–	–
C8R	–	–	–	8.4	28.9	11150	11150	14.1	46.8	3949.0	1365.0	0.2	28825.0	101.2	86.4	–	–	-12	–	–
C9D	–	–	–	8.5	32.4	10530	10530	13.8	23.6	2822.0	1040.0	0.1	8319.0	54.5	59.5	–	–	-11	–	–
C9R	–	–	–	7.8	32.4	9770	9770	26.2	26.2	3139.0	452.9	0.1	12073.0	42.3	42.2	–	–	-9	–	–
C10D	–	–	–	8.5	27.2	17480	17480	3.3	3.0	4202.0	278.0	0.1	15495.0	68.5	204.6	–	–		–	–

C10R	–	–	–	8.7	27.2	20100	20100	3.0	2.5	7795.0	305.9	0.2	26267.0	73.4	205.9	–	–		–	–
C11D	–	–	–	8.7	28.6	18120	18120	2.5	3.7	4292.0	253.6	0.1	15367.0	458.4	606.5	–	–	-4	–	–
C11R	–	–	–	8.7	28.6	20800	20800	2.6	3.2	8190.0	286.9	0.1	25357.0	445.3	595.1	–	–	-2	–	–
NEW ISLAND	–	–	–													–	–	-1	–	–
DOTN2	–	–	–	7.9	n.a.	934	-	142.1	20.7	23.7	13.2	-	640.5	2.8	10.6	–	–		–	–
DOTN5	–	–	–	8.3	23.2	6560	-	16.7	15.3	1758.1	179.2	-	4566.5	226.5	38.0	–	–	-4	–	–
DOTN6	–	–	–	8.4	24.8	6240	-	7.2	5.0	1517.0	170.3	-	4285.9	212.9	25.3	–	–	-2	–	–
DOTN7	–	–	–	8.2	24.4	6290	-	14.9	16.2	1418.0	183.0	-	3614.9	481.6	62.9	–	–	-4	–	–
DOTN8	–	–	–	8.5	25.0	11360	-	7.5	4.0	2616.7	549.7	-	6606.3	857.4	126.1	–	–	-5	–	–
DOTN9R	–	–	–	7.5	22.1	86	-	8.0	2.0	5.0	2.8	-	53.1	0.2	0.1	–	–	–	–	–
DOTNS5	–	–	–	8.4	25.0	2610	-	21.9	58.3	347.2	385.7	-	1989.8	8.5	1.7	–	–	–	–	–
DOTNF2	–	–	–	7.5	25.1	430	-	37.7	5.7	69.0	13.6	-	368.4	2.4	0.9	–	–	–	–	–
DOTNF3	–	–	–	8.5	23.9	6600		7.1	15.3	1746.4	109.8	-	4174.8	229.3	51.4	–	–	4422	–	–
DOTNFM	–	–	–	8.5	25.0	4170	-	6.9	5.4	895.6	287.5	-	2654.7	126.5	11.7	–	–	2794	–	–
DOTNF4	–	–	–	8.4	25.4	3650	-	9.7	8.7	752.8	292.9	-	2601.0	13.5	2.9	–	–	2446	–	–
DOTNF5	–	–	–	8.4	25.1	3430	-	6.6	2.6	712.0	256.0	-	2330.2	29.7	10.5	–	–	2298	–	–
ORC ISLAND	–	–	–	-	-	-	-	-	-	-	-	-	-	-		–	–	-	–	–
DOTC3	–	–	–	7.5	22.4	375	-	51.9	9.6	7.4	18.6	-	236.1	2.8	2.9	–	–	251	–	–
DOTC4	–	–	–	7.2	23.4	221	-	20.1	4.3	7.3	6.0	-	99.4	2.4	0.3	–	–	148	–	–
DOTC5	–	–	–	7.1	3.7	24.1		53.0	1.3	6.3	0.8		225.1	0.1	4.5	–	–	16	–	–
DOTC6	–	–	–	7.2	24.4	200		18.1	4.2	6.4	4.4		96.4	0.6	0.3	–	–	134	–	–
DOTC7	–	–	–	7.4	26.2	438		63.1	6.4	9.3	3.4		255.6	1.2	0.4	–	–	293	–	–
DOTC8	–	–	–	8.7	27.6	16400		11.3	1.4	5137.4	32.8		12633.1	401.2	427.2	–	–	10988	–	–
DOTC17	–	–	–	8.5	26.2	20600		10.4	16.6	5985.8	86.4		12789.3	1709.6	933.1	–	–	13802	–	–
DOTC18	–	–	–	8.7	28.4	31400		0.0	0.0	10209.1	97.8		23537.5	1807.7	1528.5	–	–	21038	–	–
DOTCM	–	–	–	8.9	28.5	30500		0.0	1.4	9535.1	47.3		21773.3	1968.2	1528.9	–	–	20435	–	–
DOTC28	–	–	–	8.1	24.6	13210		29.7	16.6	3726.7	267.9		10548.1	195.0	97.6	–	–	8851	–	–
DOTC29	–	–	–	7.4	25.0	416		29.9	6.3	52.0	7.9		262.3	3.6	0.9	–	–	279	–	–
Thata Island	–	–	–													–	–		–	–
DOTP4	–	–	–	8.1	8.1	2160		12.9	3.5	665.2	9.8		1532.9	137.6	18.2	–	–	1447	–	–

DOTP9	–	–	–	8.9	8.9	16970		2.8	0.6	4544.9	779.4		13848.2	297.6	81.7	–	–	11370	–	–
DOTP10	–	–	–	8.4	8.4	17970		7.4	1.7	5180.6	212.6		12903.9	1038.8	177.7	–	–	12040	–	–
DOTP11	–	–	–	7.5	7.5	280		23.8	6.6	17.4	5.3		161.0	0.5	0.2	–	–	188	–	–
DOTP12	–	–	–	7.8	7.8	1582		51.1	16.6	313.9	31.1		1120.6	1.2	0.3	–	–	1060	–	–
DOTT2	–	–	–	8.4	8.4	4140		9.8	21.2	1001.3	254.0		2889.0	54.8	7.6	–	–	2774	–	–
DOTT3	–	–	–	7.5	7.5	271		5.1	2.0	39.1	0.0		156.2	3.2	0.6	–	–	182	–	–
DOTT6	–	–	–	8.7	8.7	3070		5.1	6.4	670.8	195.0		2011.2	16.7	12.2	–	–	2057	–	–
DOTT9	–	–	–	8.2	8.2	3650		34.3	44.1	793.8	99.9		2473.6	116.4	6.7	–	–	2446	–	–
Huntsman-Mapila et al. (2011)																				
C1D	–	–	1/1/07	6.2	26.3	224	1.54	19.7	5.9	7.8	7.1	2.3	144.7	1.7	0.2	–	–	–	–	–
C1R	–	–	3/1/07	5.6		366	0.24	27.4	7.2	6.7	5.7	3.0	260.5	1.3	0.3	–	–	–	–	–
C2D	–	–	1/1/07	6.3	24.4	219	1.7	20.4	5.8	18.3	11.6	0.5	158.2	1.2	Nd	–	–	–	–	–
C2R	–	–	1/1/07	5.8		392	0.47	27.7	6.3	49.7	15.0	1.8	268.5	1.7	0.4	–	–	–	–	–
C3D	–	–	1/1/07	6.4	24.0	281	2.65	26.5	6.1	5.8	8.4	2.5	196.0	1.6	0.2	–	–	–	–	–
C3R	–	–	3/1/07	5.9		383	383	37.9	9.6	7.9	6.4	1.3	251.6	1.4	0.7	–	–	–	–	–
C4D	–	–	3/1/07	6.3	23.8	210	210	17.7	4.6	4.8	7.3	1.0	161.0	1.3	0.1	–	–	–	–	–
C4R	–	–	3/1/07	5.7		396	396	20.9	5.4	39.1	7.6	3.4	183.8	0.7	0.2	–	–	–	–	–
C5D	–	–	3/1/07	6.4	23.7	340	340	35	6.3	9.8	7.4	1.2	215.0	0.7	0.8	–	–	–	–	–
C5R	–	–	3/1/07	6.3		455	455	52.2	9.6	41.1	8.8	0.1	346.4	0.6	0.3	–	–	–	–	–
C6D	–	–	1/1/07	6.4	24.5	133	133	13.3	2.8	21.8	7.0	0.9	91.8	0.2	0.1	–	–	–	–	–
C6R	–	–	3/1/07	6.0		344	344	25.5	7.2	93.9	9.5	0.4	224.0	6.3	2.1	–	–	–	–	–
C7D	–	–	3/1/07	6.6	25.0	663	663	9.52	9.2	845.8	7.6	1.1	391.6	0.6	Nd	–	–	–	–	–
C7R	–	–	3/1/07	6.3		702	702	84.6	11.1	82.8	12.4	8.2	596.4	0.4	0.2	–	–	–	–	–
C8D	–	–	1/1/07	7.8	28.9	5569	5569	18.87	53.9	1894.8	825.5	0.0	4262.0	63.4	51.8	–	–	–	–	–
C8R	–	–	3/1/07	8.4		11150	11150	14.1	46.8	3949.0	1365.0	0.2	28825.0	101.2	86.4	–	–	–	–	–
C9D	–	–	1/1/07	8.5	32.4	10530	10530	13.8	23.6	2822.0	1040.0	0.1	8319.0	54.5	59.5	–	–	–	–	–
C9R	–	–	3/1/07	7.8		9770	9770	26.2	26.2	3139.0	452.9	0.1	12073.0	42.3	42.2	–	–	–	–	–
C10D	–	–	1/1/07	8.5	27.2	17480	17480	3.3	3.0	4202.0	278.0	0.1	15495.0	68.5	204.6	–	–	–	–	–
C10R	–	–	1/1/07	8.7		20100	20100	3	2.5	7795.0	305.9	0.2	26267.0	73.4	205.9	–	–	–	–	–
C11D	–	–	1/1/07	8.7	28.6	18120	18120	2.46	3.7	4292.0	253.6	0.1	15367.0	458.4	606.5	–	–	–	–	–

C11R	–	–	1/1/07	8.7	20800	20800	2.6	3.2	8190.0	286.9	0.1	25357.0	445.3	595.1	–	–	–	–	–

Explanation:

Temp (^{0}C) =Temperature in degrees centigrade, Cond=conductivity, DO =Dissolved oxygen, Alk= alkalinity, - means no value for those samples, concentrations of anions and cations are in mg/l

Table S2. Chemical and isotopic data for surface water in the Okavango Delta

Sample	Long	Lat	Date Sampled	pH	Temp	Cond	DO	Ca	Mg	Na	K	Alk	Cl	SO_4^{2-}	NO_3^-	$\delta^{18}O$	δD	TDS	DIC	$\delta^{13}C_{DIC}$
Dincer et al. (1979)																				
Xudum - Ponton	–	–	27/04/75	–	–	70	–	–	–	–	–	–	–	–	–	-0.1	-11.7	84	–	–
OR Mohembo	–	–	29/05/75	–	–	32	–	–	–	–	–	–	–	–	–	-3.9	-29.7	32	–	–
Duba (Nggokha)	–	–	13/05/75	–	–	–	–	–	–	–	–	–	–	–	–	-3.8	-28.9	28	–	–
Xakue (Boro)	–	–	10/5/75	–	–	75	–	–	–	–	–	–	–	–	–	-2.0	-19.4	40	–	–
Txatxanika KQ2 (Kwai)	–	–	15/05/75	–	–	58	–	–	–	–	–	–	–	–	–	-0.4	-11.1	76	–	–
Malalakgaka K.S3 (Santantadibe)	–	–	17/05/75	–	–	86	–	–	–	–	–	–	–	–	–	0.7	-4.2	92	–	–
Boro Junction KB4 (Boro)	–	–	5/5/75	–	–		–	–	–	–	–	–	–	–	–	-0.8	-13.0	84	–	–
Mohembo (okavango)	–	–	6/4/75	–	–	43	–	–	–	–	–	–	–	–	–	-4.4	-30.8	48	–	–
Seronga (okavango)	–	–	26/02/75	–	–	40	–	–	–	–	–	–	–	–	–	-4.0	-30.6	–	–	–
Toteng (Kunyere R.)	–	–	2/9/75	–	–	–	–	–	–	–	–	–	–	–	–	3.7	8.1	–	–	–
Tsau (Thoage R)	–	–	2/9/75	–	–	–	–	–	–	–	–	–	–	–	–	4.8	13.0	–	–	–
Maun Bidge (Thamalakane R)	–	–	8/9/75	–	–	–	–	–	–	–	–	–	–	–	–	1.9	-1.6	–	–	–
Shakawe (Okavango R)	–	–	6/9/75	–	–	–	–	–	–	–	–	–	–	–	–	-4.8	-36.2	–	–	–
Gaenga (Nggokha R.)	–	–	22/09/75	–	–	36	–	–	–	–	–	–	–	–	–	-4.0	-31.2	–	–	–
Duba(Okavango R)	–	–	22/09/75	–	–	35	–	–	–	–	–	–	–	–	–	-4.1	-32.8	–	–	–
Txatxanika(Khwaai)	–	–	24/09/75	–	–	48	–	–	–	–	–	–	–	–	–	-0.8	-14.4	–	–	–
Malalakgaka (Santantadibe)	–	–	25/09/75	–	–	120	–	–	–	–	–	–	–	–	–	5.9	19.7	–	–	–
Boro Junction KB4	–	–	25/09/75	–	–	55	–	–	–	–	–	–	–	–	–	2.5	-0.5	–	–	–
Xakue (Boro R.)	–	–	19/09/75	–	–	45	–	–	–	–	–	–	–	–	–	-0.9	-13.1	–	–	–
Chobe Road (Mpgphelo R)	–	–	20/09/75	–	–	–	–	–	–	–	–	–	–	–	–	4.9	16.9	–	–	–
Toteng (Kunyere R.)	–	–	8/11/75	–	–	–	–	–	–	–	–	–	–	–	–	8.7	31.7	–	–	–
Boteti R. (Rakops)	–	–	26/11/75	–	–	–	–	–	–	–	–	–	–	–	–	6.8	20.6	–	–	–

Boteti R. (Mopipi inlet)	–	–	26/11/75	–	–	600	–	–	–	–	–	–	–	–	–	8.0	29.6	–	–	–
Thaoge R. BE/17	–	–	29/11/75	–	–	–	–	–	–	–	–	–	–	–	–	9.7	38.9	–	–	–
Experimental area (outlet)	–	–	3/12/75	–	–	–	–	–	–	–	–	–	–	–	–	1.1	-3.5	–	–	–
Boteti R. (Rakops)	–	–	15/12/75	–	–	–	–	–	–	–	–	–	–	–	–	6.1	20.0	–	–	–
Boteti R. at Mopipi inlet	–	–	7/2/76	–	–	–	–	–	–	–	–	–	–	–	–	4.8	17.7	666	–	–
Boteti R. (Rakops)	–	–	7/2/76	–	–	–	–	–	–	–	–	–	–	–	–	4.5	12.5	–	–	–
Boteti R. (at Tsoi)	–	–	7/2/76	–	–	–	–	–	–	–	–	–	–	–	–	4.0	9.8	115	–	–
Boteti R. (at Dikwalo)	–	–	7/2/76	–	–	–	–	–	–	–	–	–	–	–	–	4.0	10.6	102	–	–
Boteti R. (at Samedupi)	–	–	7/2/76	–	–	–	–	–	–	–	–	–	–	–	–	2.6	4.8	84	–	–
Thamalakane (at Maun)	–	–	20/02/76	–	–	–	–	–	–	–	–	–	–	–	–	2.8	4.2		–	–
Xudum	–	–	24/04/75	–	–	5500	–	–	–	–	–	–	–	–	–	7.5	26.3	4900	–	–
Xudum	–	–	24/04/75	–	–	340	–	–	–	–	–	–	–	–	–	1.3	-2.2	350	–	–
Xudum	–	–	28/04/75	–	–	1000	–	–	–	–	–	–	–	–	–	0.1	-6.9	850	–	–
Xugana Lagoon	–	–	23/09/75	–	–	42	–	–	–	–	–	–	–	–	–	-2.3	-21.3	–	–	–
Gadikwe Lagoon	–	–	21/09/75	–	–	–	–	–	–	–	–	–	–	–	–	-1.5	-17.3	–	–	–
Bodumatu B.(Moremi G.R)	–	–	20/09/75	–	–	–	–	–	–	–	–	–	–	–	–	0.7	-5.1	–	–	–
Experimental area (outlet)	–	–	4/11/75	–	–	–	–	–	–	–	–	–	–	–	–	4.7	14.6	–	–	–
Experimental area (inlet)	–	–	4/11/75	–	–	55	–	–	–	–	–	–	–	–	–	4.1	9.3	–	–	–
Experimental area (outlet)	–	–	13/11/75	–	–	80	–	–	–	–	–	–	–	–	–	5.2	19.9	–	–	–
Experimental area (inlet)	–	–	13/11/75	–	–	75	–	–	–	–	–	–	–	–	–	3.5	10.1	–	–	–
Mopipi Res	–	–	26/11/75	–	–	1800	–	–	–	–	–	–	–	–	–	7.7	33.4	–	–	–
Mopipi Res	–	–	7/2/76	–	–	–	–	–	–	–	–	–	–	–	–	6.7	28.5	1123	–	–
Experimental area (outlet)	–	–	12/9/75	–	–	53	–	–	–	–	–	–	–	–	–	1.6	-2.9	–	–	–
Experimental area (inlet)	–	–	13/09/75	–	–	53	–	–	–	–	–	–	–	–	–	0.9	-6.1	–	–	–
Xudum	–	–	12/9/75	–	–	55	–	–	–	–	–	–	–	–	–	1.0	-5.5	–	–	–
Experimental area (outlet)	–	–	3/10/75	–	–	68	–	–	–	–	–	–	–	–	–	2.2	1.6	68	–	–
Experimental area (inlet)	–	–	3/10/75	–	–	55	–	–	–	–	–	–	–	–	–	1.5	-3.1	52	–	–

Experimental area (inlet)	–	–	5/12/75	–	–	–	–	–	–	–	–	–	–	–	–	5.7	18.8	–	–	–
McCarthy et al. (1993)	–	–		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
E4	–	–	6/15/05	6.2	–	0.090	–	6	1	22	7	–	–	–	–	–	–	–	–	–
E6	–	–	6/15/05	6.1	–	0.101	–	14	3	14	5	76	–	–	–	–	–	–	–	–
E8	–	–	6/15/05	6.5	–	0.478	–	52	7	49	19	233	–	–	–	–	–	–	–	–
E10	–	–	6/15/05	6.2	–	0.204	–	23	6	21	7	128	–	–	–	–	–	–	–	–
E11	–	–	6/15/05	6.8	–	0.608	–	116	19	52	9	177	–	–	–	–	–	–	–	–
E12	–	–	6/15/05	6.9	–	0.133	–	21	3	12	8	102	–	–	–	–	–	–	–	–
F1	–	–	6/15/05	6.8	–	0.044	–	68	14	62	5	302	5	5.0	–	–	–	–	–	–
F2	–	–	6/15/05	7.2	–	1.410	–	56	41	220	69	749	27	26.0	–	–	–	–	–	–
F3	–	–	6/15/05	8.6	–	4.110	–	6	5	1750	89	3196	76	140.0	–	–	–	–	–	–
F4	–	–	6/15/05	9.3	–	9.270	–	3	1	4200	314	5182	320	560.0	–	–	–	–	–	–
F5	–	–	6/15/05	8.5	–	2.500	–	8	18	700	52	1501	–	–	–	–	–	–	–	–
F9	–	–	6/15/05	8.9	–	0.386	–	4	1	1500	75	2013	–	–	–	–	–	–	–	–
F11	–	–	6/15/05	5.7	–	0.120	–	3	1	8	3	27	–	–	–	–	–	–	–	–
A9	–	–	6/15/05	7.4	–	0.741	–	26	15	160	59	556	5	5.0	–	–	–	–	–	–
B swamp	–	–	6/15/05	6.3	–	0.076	–	7	2	9	5	42	–	–	–	–	–	–	–	–
B1	–	–	6/15/05	7.1	–	0.223	–	84	6	15	9	239	–	–	–	–	–	–	–	–
B3	–	–	6/15/05	8.0	–	3.800	–	24	128	2300	438	5700	–	–	–	–	–	–	–	–
B4	–	–	6/15/05	8.6	–	13.800	–	10	9	5200	1070	9605	–	–	–	–	–	–	–	–
B5	–	–	6/15/05	8.6	–	10.400	–	5	10	4000	496	4834	62	8.0		–	–	–	–	–
B7	–	–	6/15/05	6.8	–	0.225	–	14	6	13	4	87	–	–	–	–	–	–	–	–
B8	–	–	6/15/05	6.9	–	0.474	–	100	4	16	8	193	–	–	–	–	–	–	–	–
C swamp	–	–	6/15/05	6.9	–	0.064	–	5	1	6	4	32	–	–	–	–	–	–	–	–
C1	–	–	6/15/05	7.0	–	0.203	–	60	4	13	7	166	–	–	–	–	–	–	–	–
C3	–	–	6/15/05	7.1	–	0.726	–	56	32	125	34	367	–	–	–	–	–	–	–	–
C4	–	–	6/15/05	7.8	–	1.020	–	16	16	160	196	712	–	–	–	–	–	–	–	–

C6	–	–	6/15/05	7.1	–	0.360	–	56	22	13	42	224	–	–	–	–	–	–	–	–
C7	–	–	6/15/05	7.4	–	0.630	–	88	36	75	38	297	–	–	–	–	–	–	–	–
D Swamp	–	–	6/15/05	6.3	–	0.130	–	6	3	9	7	57	–	–	–	–	–	–	–	–
D2	–	–	6/15/05	6.9	–	0.433	–	80	10	24	28	168	–	–	–	–	–	–	–	–
D4	–	–	6/15/05	8.1	–	5.300	–	20	30	1550	164	2812	320	5.0	–	–	–	–	–	–
D5	–	–	6/15/05	7.1	–	1.020	–	72	10	200	10	379	–	–	–	–	–	–	–	–
D Pan	–	–	6/15/05	7.8	–	0.770	–	24	16	185	50	360	–	–	–	–	–	–	–	–
Huntsman-Mapila at al. (2006)																	–	–	–	–
UPO1a	–	–	2/2/03	6.5	28.5	35.9	5.7	4.1	0.9	2	2	25.6	0.28	0.2	–	–	–	–	–	–
UP02a	–	–	2/3/03	6.4	29.1	39	0.7	4.3	0.9	2	2	26.8	0.48	0.2	0.45	–	–	–	–	–
LP03a	–	–	2/7/03	6.5	27.3	63	2.3	5.9	1.5	3	3	27.7	0.88	0.3	0.2	–	–	–	–	–
LP04a	–	–	2/6/03	6.6	28.7	49.2	2.5	6.5	1.5	2	1	35.4	0.24	0.1		–	–	–	–	–
LP05a	–	–	2/7/03	5.5	27.2	51.2	0.7	5.9	1.4	3	3	31.7	0.24	0.3	0.03	–	–	–	–	–
MC06a	–	–	2/11/03	7.0	29	51.5	5.1	5.8	1.2	3	2	34.2	0.61	0.3	0.6	–	–	–	–	–
MC07a	–	–	2/12/03	7.2	28.8	51.7	5.2	5.9	1.2	3	2	34.2	0.29		0.04	–	–	–	–	–
MC08a	–	–	2/11/03	7.2	28.9	49.7	5.5	5.7	1.1	3	2	31.7	0.35		0.01	–	–	–	–	–
B09a	–	–	2/14/03	6.6	27.9	75.2	1.1	8.4	1.7	5	3	50	0.31	0.1	0.84	–	–	–	–	–
Atekwana, (2008) unpublished	–	–														–	–	–	–	–
Okavango River Mohembo	–	–	6/25/08	4.9	17.62	30	–	2.5	2.3	1.8	1.3	13	0.61	0.5	–	–	–	19	–	-9.0
Okavango River Drotsky Cabins	–	–	6/25/08	5.1	17.84	30	–	2.6	2.4	1.8	1.4	14	0.61	0.3	–	–	–	19	–	-9.2
Okavango River Mogotlho-Sangoshe	–	–	6/26/08	5.4	17.31	30	–	2.9	2.4	2.0	1.3	14	0.49	0.4	–	–	–	20	–	-8.9
Okavango River Sepupa	–	–	6/25/08	5.0	16.72	32	–	2.8	2.4	2.1	1.2	15	0.39	0.3	–	–	–	23	–	-9.2
Okavango River Seronga	–	–	6/26/08	5.2	17.42	32	–	3.2	2.5	2.4	1.3	15	0.33	0.1	–	–	–	22	–	-9.8
Okavango River Qurube	–	–	6/24/08	5.1	15.12	34	–	3.8	2.5	2.8	1.4	18	0.39	0.2	–	–	–	22	–	-5.0
Thamalakane River Maun	–	–	6/24/08	6.8	19.02	90	–	10.6	3.7	11.6	3.6	44	0.57	0.1	–	–	–	55	–	-9.5
Khwai River - Mababi	–	–	6/20/08	7.4	20.07	154	–	10.3	4.1	16.9	6.5	68	1.72	0.5	–	–	–	94	–	-5.6
Mababe Marsh	–	–	6/20/08	8.0	19.02	172	–	11.1	4.5	19.2	7.6	76	1.71	0.5	–	–	–	104	–	-6.8

Okavango at Mohembo	021°47.207'E	18°16.647' S	7/10/12	4.8	15.97	37	7.8	3.76	0.89	1.78	1.43	16.4	0.50	0.5	–	–	–	24	3.1	-9.3
Okavango at Drotkosky	021°53.133'E	18°24.824' S	7/10/12	4.8	16.64	37	7.6	3.72	0.87	1.74	1.40	16.4	0.47	0.4	–	–	–	24	3.4	-10.0
Okavango at Swamp Stop (10:00)	021°53.138'E	18°24.824' S	7/10/12	4.4	15.52	40	5.9	3.75	0.98	1.84	1.21	17.6	0.40	0.2	–	–	–	26	3.6	-9.9
Seronga 1	022°24.072'E	18°49.756' S	7/12/12	4.2	15.48	39	5.2	3.95	1.06	1.98	1.26	18.4	0.15	0.1	–	–	–	25	4.8	-10.9
Seronga 2	022°24.647'E	18°50.920' S	7/12/12	4.5	15.38	41	5.7	3.79	1.03	1.95	1.21	18.7	0.20	0.1	–	–	–	26	5.2	-10.8
Seronga 3	022°27.998'E	18°53.080'S	7/12/12	4.2	15.71	39	6.2	3.74	1.03	1.91	1.19	18.3	0.24	0.1	–	–	–	25	4.9	-10.7
Seronga 4	022°30.874'E	18°56.590'S	7/12/12	4.3	15.76	39	6.3	3.91	1.06	2.00	1.20	18.2	0.16	0.1	–	–	–	25	4.7	-9.9
Jao River	022°34.501'E	18°59.183' S	7/12/12	4.4	15.51	39	7.1	3.94	1.08	1.92	1.18	18.1	0.17	0.1	–	–	–	25	4.4	-9.5
Boro River 7	023°07.558'E	19°32.194'S	7/20/12	6.1	16.51	56	6.1	4.81	1.39	4.01	1.77	25	0.33	0.1	–	–	–	37	6.3	-9.7
Boro River 6	023°08.794'E	19°31.463'S	7/20/12	6.4	16.38	75	5.6	6.50	1.82	6.08	2.85	33	0.62	0.1	–	–	–	48	8.3	-9.2
Boro River 5	023°13.069'E	19°36.474' S	7/20/12	6.6	14.76	75	6.1	6.90	1.83	5.73	2.70	34	0.73	0.1	–	–	–	48	8.1	-9.5
Boro River 4	023°13.396'E	19° 42.205'S	7/20/12	6.1	15.54	60	6.3	5.73	1.57	4.29	1.94	27	0.51	0.1	–	–	–	43	6.3	-9.0
Boro River 3	023°17.550'E	19°46.549'S	7/20/12	6.1	15.54	67	5.7	5.99	1.72	4.80	2.19	28	0.47	0.1	–	–	–	44	6.7	-8.1
Boro River 2	023°22.065'E	19°48.578'S	7/20/12	6.7	15.35	78	5.2	6.68	1.97	5.94	2.81	33	0.67	0.0	–	–	–	51	7.8	-9.1
Boro River 1	023°29.208'E	19°53.975'S	7/20/12	6.7	14.52	87	6.1	7.44	2.20	6.76	3.25	43	0.64	0.0	–	–	–	57	9.7	-7.7
Khwai river at Mababevillage	023°59.463'E	19°10.712' S	7/8/12	6.8	17.19	126	8.1	10.39	3.03	11.82	6.57	59.9	1.85	0.1	–	–	–	82	12.2	-10.2
Khwai river at Mogotlho	023°57.277'E	19°14.422' S	7/8/12	6.8	17.46	125	7.2	9.30	2.96	11.12	6.04	59.8	1.88	0.1	–	–	–	81	11.2	-4.7
Thamalakane at Maun Bridge	023°29.764'E	19°56.524' S	7/15/12	6.7	16.12	93	7.6	8.30	2.34	7.40	3.88	42.6	0.80	0.2	–	–	–	61	9.3	-7.0
Boronyane (bridge 3)	023°28.953'E	19°56.582' S	7/15/12	7.3	17	104	8.6	9.37	2.77	8.79	4.79	51.1	1.20	0.1	–	–	–	66	9.5	-5.6
Tsau Bridge	022°28.135'E	20° 11.015' S	7/16/12	6.6	14.39	88	8.5	8.82	2.56	6.37	4.10	40.6	0.18	1.12	–	–	–	57	8.1	-5.1
Shashe (2nd bridge)	023°23.116'E	20°01.868'S	7/15/12	7.6	15.75	114	8.7	10.01	2.93	8.88	4.84	53.4	1.18	0.09	–	–	–	74	9.7	-6.4
Nhabe at Komana village	023°13.832'E	20°11.839' S	6/30/12	7.1	17.9	112	3.4	10.57	2.82	8.44	5.13	44.4	1.19	0.08	–	–	–	73	9.4	-8.1
Kunyere river at toteng village	022°56.761'E	20°21.601' S	6/30/12	7.0	16.91	124	3.9	10.41	3.04	10.31	5.61	60.2	1.31	0.09	–	–	–	80	11.7	-8.9
Nhabe at toteng village	022°57.320'E	20°21.895'S	6/30/12	7.2	17	118	3.8	9.80	2.92	8.85	5.56	55.9	1.31	0.13	–	–	–	76	9.4	-6.0
Boteti at Motopi	024°07.627'E	20°12.734'S	7/22/12	7.0	14.56	115	7.2	10.23	2.90	8.90	5.42	55	1.16	0.07	–	–	–	75	11.0	-6.3
Boteti at Khumaga	024°30.897'E	20°28.327'S	7/22/12	7.7	14.85	135	8.3	11.48	3.15	9.40	6.13	58	1.48	0.10	–	–	–	88	12.6	-6.0
Boteti at Toromoja	024°38.551'E	21°07.129' S	7/22/12	7.6	14.88	152	8.5	14.68	3.69	11.01	7.61	61	1.76	0.20	–	–	–	99	12.3	-5.8

Nhabe at Toteng 7-2-12	–	–	7/22/12	–	–	Nd	–	–	–	–	–	–	2.19	0.54	–	–	–	–	–	–
Kunyere at Toteng 6-30-12	–	–	6/30/12	–	–	Nd	–	–	–	–	–	–	1.48	0.15	–	–	–	–	–	–
Thamalakane at Sedia	–	–	6/30/12	–	–	Nd	–	8.50	2.49	8.03	–	–	1.13	0.10	–	–	–	–	–	–
Mohembo	21°47'11.49"E	18°16'37.58"S	6/30/12	6.3	14.24	37	8.5	4.26	0.91	2.11	1.67	17.4	0.35	0.25	–	-4.6	-32.2	24	2.8	-10.6
Shakawe	21°50'47.01"E	18°21'36.44"S	7/16/12	6.5	14.57	37	7.7	4.25	0.91	2.06	1.62	17.5	0.38	0.28	–	-5.7	-36.2	24	3.3	-11.4
Drotsky	21°52'58.59"E	18°24'52.26"S	7/14/12	6.3	14.68	37	8.1	4.22	0.92	2.07	1.73	17.2	0.40	0.26	–	-5.7	-36.5	24	3.3	-11.5
Mogotlho	22°11'54.09"E	18°44'45.46"S	7/15/12	5.4	15.04	40	6.8	4.53	1.04	2.16	1.72	17.9	0.37	0.20	–	-4.7	-29.3	25	3.5	-10.6
Sepopa	22°11'54.09"E	18°44'45.46"S	7/15/12	6.7	14.65	42	4.5	4.45	1.16	2.23	1.64	18.9	0.31	0.16	–	-4.7	-29.5	28	4.9	-11.0
Seronga #3	22°21'21.90"E	18°48'23.30"S	7/12/12	4.9	15.09	41	5.4	4.45	1.11	2.30	1.61	18.1	0.24	0.14	–	-2.5	-23.7	26	5.0	-11.2
Seronga #4	22°22'28.70"E	18°48'51.70"S	7/12/12	5.1	15.17	41	5.2	4.41	1.13	2.27	1.60	17.9	0.35	0.13	–	-2.6	-23.8	26	4.2	-11.2
Seronga #1	22°23'53.28"E	18°49'17.69"S	7/12/12	5.2	15.29	43	5.7	4.44	1.16	2.32	1.69	18.3	0.41	0.13	–	-1.7	-19.9	31	4.4	-11.5
Seronga	22°15'16.69"E	19°14'32.61"S	7/10/12	6.4	15.01	45	4.3	4.73	1.21	2.53	1.81	21.1	0.35	0.12	–	-3.8	-26.4	29	5.0	-10.8
Seronga #2	22°24'6.80"E	18°49'47.40"S	7/11/12	5.2	15.36	41	5.7	4.54	1.15	2.50	1.77	18.4	0.39	0.13	–	-2.5	-24.6	28		
Lower chan #1	23°10'39.09"E	19°32'57.69"S	14/07/11	6.7	15.57	81	4.1	7.65	1.93	6.18	3.28	34.7	0.57	0.12	–	1.2	-6.0	53	8.4	-9.9
Lower chan #2	23°17'53.77"E	19°46'40.24"S	14/07/11	7.0	16.15	68	7.0	6.26	1.71	5.29	2.91	28.9	0.41	0.08	–	-1.9	-15.0	44	6.8	-10.4
Lower chan #3	23°24'3.23"E	19°50'42.41"S	14/07/11	6.9	16.4	81	5.8	7.83	2.06	6.32	3.33	36	0.53	0.08	–	-1.0	-15.6	53	7.8	-10.1
Low chan #4 _boro channel.	23°29'14.52"E	19°53'58.91"S	14/07/11	7.1	16.29	94	8.6	8.44	2.28	7.13	3.71	40.7	0.68	0.08	–	-0.2	-11.0	62	8.0	-7.3
Tsaua river	22°28'7.11"E	20°11'1.62"S	18/07/11	6.4	14.56	75	9.3	36.73	2.77	4.72	3.10	37	0.15	1.21	–	0.7	-8.4	49	6.0	-9.1
Kunyere at toteng br	22°56'45.84"E	20°21'33.62"S	29/6/11	6.8	15.15	137	10.9	12.20	3.29	11.64	5.96	69.6	1.31	0.21	–	0.9	-6.5	89	12.9	-8.9
Thamalakane maun bridge	23°29'46.02"E	19°56'31.03"S	3/7/11	6.5	17.09	106	11.0	9.31	2.62	8.33	4.43	40	0.93	0.08	–	0.3	-9.7	69	10.1	-7.9
Out of town bridg	23°23'3.14"E	20° 1'50.75"S	2/7/11	6.9	16.35	129	10.7	11.67	3.24	10.65	5.64	56	1.39	0.09	–	1.2	-5.4	84	11.1	-7.5
Than at komana	23°13'50.90"E	20°11'49.37"S	4/8/11	6.7	16.21	113	12.4	19.07	2.97	9.25	5.11	53	1.09	0.09	–	0.5	-6.6	73	10.0	-8.2
Than at toteng	22°57'22.43"E	20°21'54.77"S	–	6.8	15.7	119	12.6	10.00	2.66	10.31	5.81	57.1	1.37	0.19	–	0.0	-5.2	78	10.8	-7.8
Kwai r mogotlho	23°57'16.23"E	19°14'25.26"S	6/7/11	6.5	15.45	149	11.4	10.33	3.29	16.78	6.39	66	2.40	0.09	–	0.0	-5.0	97	13.7	-6.5
Kwai r mababe	23°59'27.61"E	19°10'43.66"S	4/7/11	6.8	14.09	151	10.6	10.34	3.40	17.09	6.58	68	2.25	0.09	–	0.0	-5.2	98	13.7	-7.2
Boteti r motopi	24° 7'39.00"E	20°12'45.02"S	7/20/11	6.7	16.3	119	10.2	11.16	2.88	9.44	5.23	54	1.16	0.09	–	1.7	-1.9	77	11.5	-7.5
Boteti r toromaja	24°38'31.76"E	21° 7'7.58"S	7/20/11	6.9	17.56	150	9.0	14.68	3.41	11.77	7.33	63	1.95	0.31	–	2.0	2.6	97	13.4	-8.6

Akoko et al. (2012)

Low water																				
Mohembo	21°47'12.04"E	18°16'37.98"S	1/27/12	6.3	29.4	-	4.6	4.99	1.21	2.76	2.01	22.8	0.12	0.09	0.5	-7.2	-47.3	32	6.0	-7.9
Shakawe	21°50'46.70"E	18°21'36.94"S	1/27/12	6.5	28.5	-	3.9	4.47	1.14	2.73	2.03	25.2	0.11	0.14	0.12	-7.0	-47.4	32	6.8	-8.3
Drostky	21°53'05.19"E	18° 24'50.82"S	1/27/12	5.7	28.8	-	3.3	4.64	1.15	2.71	2.1	22.8	0.09	0.08	0.18	-6.5	-46.9	32	7.8	-8.1
Mogoto	22°09'19.01"E	18°32'01.49"S	1/26/12	6.0	31.3	-	2.3	6.52	1.38	1.86	1.4	28.8	0.11	0.00	0.23	-2.8	-22.6	40	8.3	-6.8
Mogacha	22°12'04.77"E	18°36'25.30"S	1/27/12	6.0	28.4	-	2.2	4.81	1.06	2.41	2.84	24	0.26	0.00	0.11	-5.5	-38.3	35	7.5	-6.7
Sepopa	22°11'54.09"E	18°44'45.46"S	1/27/12	5.1	27.3	-	2.5	5.79	1.29	2.48	2.69	28.8	0.26	0.01	0.31	-4.7	-34.1	38	7.4	-5.3
Seronga	22°24'52.72"E	18°49'18.87"S	1/27/12	5.7	27.9	-	2.2	6.77	1.53	2.43	2.13	31.2	0.25	0.00	0.16	-3.2	-27.9	41	11.3	-4.2
Boro	23°29'14.52"E	19°53'58.91"S	1/29/12	7.2	30.5	-	6.7	10.38	2.7	8.47	3.77	57.6	0.21	0.01	0.26	1.0	-4.0	75	14.0	-6.3
Maun	23°29'46.05"E	19°56'31.18"S	1/30/12	7.1	31.1	-	4.9	7.9	2.55	8.52	3.76	60	0.19	0.00	0.13	1.1	9.1	75	13.4	-6.6
Xudum	22°56'46.27"E	20°21'33.26"S	2/2/12	7.6	31.4	-	6.8	12.61	2.96	10.43	4.61	73.2	0.23	0.00	0.11			89	15.0	-6.2
Komana	23°13'51.00"E	20° 11'49.37"S	2/4/12	7.5	29.4	-	5.7	12.43	2.8	8.26	4.57	66	0.22	0.00	0.21	3.3	4.2	83	11.0	-1.9
Mababe	23°59'27.61"E	19°10'43.66"S	1/12/14	7.1	28.1	-	5.2	12.46	2.55	11.69	5.81	64.8	0.65	0.00	0.16	0.0	-6.8	84	14.0	-5.1
Highwater																				
Mohembo	21°47'12.04"E	18°16'37.98"S	21/07	5.6	16.61	-	9.9	3.92	1.01	1.79	1.42	11	0.60	0.30	0.16	-3.6	-30.5	22	0.7	-8.4
Shakawe	21°50'46.70"E	18°21'36.94"S	22/07	5.5	16.56	-	7.1	3.53	1.21	1.66	1.25	18	0.40	0.40	0.15	-4.6	-33.8	23	0.7	-10.8
Drostky	21°53'05.19"E	18°24'50.82"S	22/07	6.1	16.62	-	7.4	3.56	1.24	1.84	1.45	16.8	0.50	0.40	0.76	-4.4	-34.7	23	0.6	-9.6
Mogacha	22°12'04.77"E	18°36'25.30"S	21/07	5.6	16.7	-	7.4	3.76	1.42	1.84	1.34	19.2	0.40	0.30	0.27	-4.5	-33.2	24	2.9	-10.4
Sepopa	22°11'54.09"E	18°44'45.46"S	23/07	5.7	16.03	-	7.2	4.33	1.57	1.81	1.43	12	0.30	0.30	0.08	-3.6	-29.4	26	5.3	-10.9
Seronga	22°24'52.72"E	18°49'18.87"S	21/07	5.1	16.73	-	6.6	4.23	1.74	2.04	1.48	19.2	0.40	0.30	0.07	-4.1	-32.4	28	5.6	-12.3
Lagoon	22°15'16.69"E	19°14'32.61"S	18/07	6.8	19.56	-	8.8	8.88	3.11	2.13	2.48	36	0.40	0.20	0.10	0.1	-10.7	47	8.6	-7.7
Boro	23°29'14.52"E	19°53'58.91"S	16/07	7.1	17.6	-	13.1	8.49	3.30	3.62	3.69	39.6	0.70	0.30	0.14	-0.7	-13.2	80	9.7	-6.6
Maun	23°29'46.05"E	19°56'31.18"S	16/07	7.2	17.18	-	11.1	8.68	3.31	6.62	3.74	54	0.90	0.30	0.09	-0.5	-14.1	63	9.6	-7.0
Xudum	22°56'46.27"E	20°21'33.26"S	17/07	7.3	15.01	-	13.9	10.64	4.15	9.15	4.48	52.8	0.90	0.30	0.16	-0.6	-14.0	80	11.1	-8.0
Toteng	22°57'21.05"E	20°21'54.37"S	17/07	7.4	15.5	-	11.5	10.23	3.89	7.73	4.72	58.8	0.90	0.30	0.12	0.4	-8.4	75	9.9	-6.3
Komana	23°13'51.00"E	20°11'49.37"S	17/07	7.0	16.19	-	16	9.82	3.80	7.62	4.57	62.4	1.00	0.30	0.36	0.1	-9.6	71	7.8	-6.4

Mogoltho	23°57'16.03"E	19°14'25.55"S	18/07	7.0	16.44	-	9.8	9.55	4.47	16.97	6.09	97.2	2.10	0.20	0.01	0.8	-1.0	101	12.3	-6.3
Mababe	23°59'27.61"E	19°10'43.66"S	18/07	6.7	15.64	-	11.1	9.91	4.65	17.59	6.35	98.4	2.30	0.20	0.01	0.1	0.9	103	15.5	-6.3
Boteti	24°07'39.04"E	20°12'45.05"S	29/08	6.5	17.77	-	11	11.36	4.18	8.44	5.13	72	1.20	0.20	0.33	0.6	-3.6	82	16.3	-6.5

Explanation:

Temp (^{0}C) =Temperature in degrees centigrade, Cond=conductivity, DO =Dissolved oxygen, Alk= alkalinity, **-** means no values for those samples, concentrations of anions and cations are in mg/l

VITA

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Presentations and Abstracts:

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